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Training Command

NAVEDTRA 10277
September 1985
0502-LP-051-3800

Rate Training
Manual

# Fire Controlman Second Class

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STACKS

Although the words "he," "him," and "his" are used sparingly in this manual to enhance communication, they are not intended to be gender driven nor to affront or discriminate against anyone reading *Fire Controlman Second Class*, NAVEDTRA 10277.

Naval Education And Training Program Development Center

# FIRE CONTROLMAN SECOND CLASS

## NAVEDTRA 10277

DEPARTMENT OF THE NAVY ★ CHIEF OF NAVAL EDUC AND TNG

*1985 Edition Prepared by*
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# PREFACE

This rate training manual (RTM), *Fire Controlman Second Class* (FC2), NAVEDTRA 10277, is intended to provide enlisted personnel with background information necessary for advancement to the rate of Fire Controlman Second Class. This includes information on servomechanisms, analog computers, digitial computers, radar principles, microwave components, cooling and dry air systems, battery alignment, collimation, and maintenance.

Designed for individual study vice formal classroom instruction, the RTM provides subject matter that relates directly to the Occupational Sdtandards for FC2. A separate Nonresident Career Course (NRCC) provides the usual way of satisfying the requirements for completing the RTM. It consists of a set of assignments which include learning objectives and supporting questions designed to help students complete the RTM. You may find it beneficial to browse the entire training package and to read the front matter to the NRCC before you begin serious study.

This training manual was prepared by the Naval Education and Training Program Development Center, Pensacola, Florida, for the Chief of Naval Education and Training. Special credit is given to the following commands for their reviews during the preparation of the manual: Naval Sea Systems Command, Washington, D.C.; Naval Ship Weapon System Engineering Station, Port Hueneme, California; AEGIS Combat Systems Engineering Development Site, Moorestown, New Jersey; Naval Guided Missiles School, Dam Neck, Virginia; Fleet Combat Training Center, Atlantic, Dam Neck, Virginia; Combat Systems Technical Schools Command, Mare Island, California; and Service Schools Command, Great Lakes, Illinois.

1985 Edition

**Stock Ordering No.**
**0502-LP-051-3800**

Published by
NAVAL EDUCATION AND TRAINING PROGRAM
DEVELOPMENT CENTER

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON, D.C.: 1985

# THE UNITED STATES NAVY

## GUARDIAN OF OUR COUNTRY

The United States Navy is responsible for maintaining control of the sea and is a ready force on watch at home and overseas, capable of strong action to preserve the peace or of instant offensive action to win in war.

It is upon the maintenance of this control that our country's glorious future depends; the United States Navy exists to make it so.

## WE SERVE WITH HONOR

Tradition, valor, and victory are the Navy's heritage from the past. To these may be added dedication, discipline, and vigilance as the watchwords of the present and the future.

At home or on distant stations we serve with pride, confident in the respect of our country, our shipmates, and our families.

Our responsibilities sober us; our adversities strengthen us.

Service to God and Country is our special privilege. We serve with honor.

## THE FUTURE OF THE NAVY

The Navy will always employ new weapons, new techniques, and greater power to protect and defend the United States on the sea, under the sea, and in the air.

Now and in the future, control of the sea gives the United States her greatest advantage for the maintenance of peace and for victory in war.

Mobility, surprise, dispersal, and offensive power are the keynotes of the new Navy. The roots of the Navy lie in a strong belief in the future, in continued dedication to our tasks, and in reflection on our heritage from the past.

Never have our opportunities and our responsibilities been greater.

# CONTENTS

CHAPTER Page

1. Servomechanisms ........................................ 1-1
2. Analog Computing Elements ............................ 2-1
3. Digital Computers ........................................ 3-1
4. Radar Principles .......................................... 4-1
5. Microwave Components ................................. 5-1
6. Cooling and Dry-Air Systems ........................... 6-1
7. Battery Alignment ........................................ 7-1
8. Collimation ................................................ 8-1
9. Maintenance .............................................. 9-1

APPENDIX

I. Glossary .................................................. AI-1
II. References ............................................. AII-1
INDEX ........................................................ I-1

# FIRE CONTROLMAN SECOND CLASS
# OCCUPATIONAL STANDARDS

| NUMBER | OCCUPATIONAL STANDARD | CHAPTER |
|---|---|---|
| FIRE CONTROLMAN SECOND CLASS (FC2) | | |
| 14 ELECTRONICS MAINTENANCE | | |
| 14350 | TEST AND ALIGN RADAR RANGING CIRCUITS | 4, 9 |
| 14632 | MEASURE RECEIVER SENSITIVITY | 4, 5, 9 |
| 14633 | ALIGN RADAR TRANSMITTERS AND RECEIVERS | 4, 5, 9 |
| 14634 | COLLIMATE RADARS | 4, 5, 8 |
| 14640 | DETECT AND CONTROL THE ADVERSE EFFECTS OF TEMPERATURE AND HUMIDITY ON EQUIPMENT | 4, 6, 9 |
| 14955 | LOCALIZE EQUIPMENT CASUALTIES TO SYSTEMS, SUB-SYSTEMS, CIRCUITS AND PARTS | 1, 2, 3, 4, 5, 6, 7, 8, 9 |
| 24 ELECTRICAL MAINTENANCE | | |
| 24020 | TEST, REPLACE AND ALIGN FIRE CONTROL SYSTEMS DATA TRANSMISSION/INDICATING DEVICES | 1, 2, 3, 4, 9 |
| 24030 | PERFORM CORRECTIVE MAINTENANCE ON FIRE CONTROL SWITCHBOARDS | 1, 9 |
| 26 ANALOG/DIGITAL COMPUTER | | |
| 26249 | CONDUCT SYSTEM OPERABILITY TESTS | 1, 2, 3, 4, 5, 6, 7, 8, 9 |
| 29 MECHANICAL MAINTENANCE/OPERATION-ORDNANCE EQUIPMENT | | |
| 29040 | SELECT/USE ELECTRONIC COUNTER COUNTERMEASURES (ECCM) TECHNIQUES | 4, 5 |
| 29545 | READ AND PLOT DATA DURING BATTERY ALIGNMENT | 1, 2, 7, 8, 9 |

| NUMBER | OCCUPATIONAL STANDARD | CHAPTER |
|---|---|---|
| 46 PUBLICATIONS | | |
| 46403 | ENTER CHANGES TO TECHNICAL PUBLICATIONS | 9 |
| 51 MAINTENANCE PLANNING AND QUALITY ASSURANCE | | |
| 51114 | COMPLETE PLANNED MAINTENANCE SYSTEM (PMS) FEEDBACK REPORTS | 9 |
| 54 LOGISTICS SUPPORT | | |
| 54057 | POST CHANGES TO COSAL | 9 |
| 54907 | INVENTORY INSTALLED EQUIPMENT AND VERIFY SPARE PARTS SUPPORT IN COSAL | 9 |
| 54913 | MAINTAIN SHIP'S ARMAMENT INVENTORY LIST (SAIL) | 9 |
| 92 ELECTRO/MECHANICAL MAINTENANCE | | |
| 92454 | INSTALL ORDALTS AND MODIFICATIONS TO EQUIPMENT | 1, 2, 3, 4, 5, 6, 9 |
| 92456 | ISOLATE MALFUNCTIONS IN ANTENNA ROTATION DRIVES AND SEARCH RADAR SYSTEMS, AND PERFORM CORRECTIVE MAINTENANCE | 1, 2, 4, 9 |
| 92458 | ISOLATE MALFUNCTIONS IN WEAPONS DIRECTION/DESIGNATION SYSTEMS AND PERFORM CORRECTIVE MAINTENANCE | 1, 2, 3, 4, 5, 6, 9 |
| 92460 | ISOLATE MALFUNCTIONS IN DIRECTORS AND PERFORM CORRECTIVE MAINTENANCE | 1, 2, 3, 4, 5, 6, 9 |
| 92462 | ISOLATE MALFUNCTIONS IN STABLE ELEMENTS AND PERFORM CORRECTIVE MAINTENANCE | 1, 2, 9 |
| 94 MECHANICAL MAINTENANCE | | |
| 94800 | REPAIR AND REPLACE COMPONENTS OF LIQUID COOLANT SYSTEMS | 6, 9 |
| 94802 | REPAIR AND REPLACE COMPONENTS OF LOW PRESSURE DRY AIR SYSTEMS | 6, 9 |

# CHAPTER 1

# SERVOMECHANISMS

Servomechanisms, called servos for short, have countless applications in fire control. Directors, radar antennas, computing devices, missile launchers, and gun mounts are positioned by servos. The operation of modern fire control equipment is almost fully automatic and largely dependent on data from remote sources. To obtain smooth, continuous, and accurate operation, the information flow is normally best controlled by synchros. But the power produced by transmission devices such as synchros is not large enough to do appreciable amounts of work. Therefore, servo systems are necessary for the precise control required by our fire control systems. A sound understanding of the principles of servomechanisms is a must for the Fire Controlman.

A *control system* is a group of components, systematically organized to perform an end function. Generally, a control system has a large power gain between input and output. Systems range from simple motor control systems to very complex computer-controlled fire control systems.

## CONTROL SYSTEMS

There are many types and classes of control systems, but all of them fall into two basic categories: OPEN LOOP CONTROL SYSTEMS and CLOSED LOOP CONTROL SYSTEMS. Each system can be mechanical, electrical, pneumatic or hydraulic. The closed loop control system in particular, being automatic in nature, is further classified by the function it serves; for example, controlling the position, velocity, or acceleration of the load being driven.

### BASIC OPERATING PRINCIPLE OF THE OPEN LOOP SYSTEM

An open loop control system is controlled, directly and solely, by an input signal. A simple system of this type is an amplifier and motor in which the amplifier receives a low-level input signal that is amplified to drive the motor that performs some task. Note that the motor output, the shaft velocity, is not directly related to the input signal. Therefore, the input signal to the amplifier remains the same regardless of the shaft velocity, even though the shaft velocity may vary under different load conditions.

Open loop control systems generally require a human operator to vary the input signal to meet the end requirement. Manually operated machine tool drives and controls are examples. The human operator continually makes adjustments to speed and travel.

### BASIC OPERATING PRINCIPLE OF A CLOSED LOOP SYSTEM (SERVO)

The closed loop control system is more commonly called *servo* system. The word *servo* is derived from the Latin *servus* meaning slave.

A *servo* will follow a command, with no need for a human operator to continually adjust the input to meet varying output conditions.

To be classified as a servo, a control system must have the following capabilities:

- Be capable of accepting an order that defines the desired result.

- Be capable of evaluating the present conditions.

- Be able to compare the desired result with the present conditions and obtain a difference or an error signal.

- Be able to issue a correcting order, determined by the error signal, that will properly change the existing conditions to the desired result.

- Have the means to obey the correcting order.

The operation of a servo system is controlled by the *error signal.* The *error signal* is derived from the algebraic sum of the input or command signal and the response signal. Response is a measurement of the output of the servo, which may be position, acceleration, or velocity. The command signal and response signals must always be in opposition so that the algebraic sum will be zero when the load meets the command conditions. Thus, if the command is a positive direct current (dc) signal, the response must be a negative dc signal. If the command signal is alternating current (ac), the response must be 180 degrees out of phase.

For example, if an input signal, at the point where the signals are summed, is measured as +10 volts and the response signal measured −5 volts, the error signal would be +5 volts (the algebraic sum of +10 volts and −5 volts). Alternately, if the input was −10 volts and the feedback was +5 volts, the error signal would be −5 volts.

In both examples, the load (director, gun mount, launcher, and so forth) is going to be driven until the response signal is equal and opposite to the input signal.

Response is the key to the successful operation of a servo. The response signal enables us to precisely control fire control equipments in response to orders or data from some remote station. Response, however, is not all that's necessary for a true servo. In fact, response satisfies only one of the five requirements of a servo. It provides the means of evaluating present conditions and is only a part of the complete servo loop. Let's take a closer look at a complete servo loop. We'll start with an analysis of the characteristics of servomechanisms.

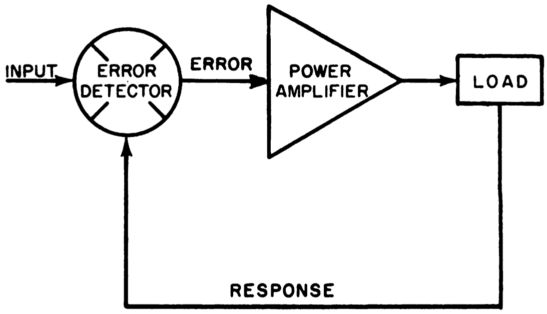

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**Figure 1-1.—Diagram of an elementary servo.**

### Servomechanism Characteristics

A SERVO IS A CONTROL DEVICE. The basic job of the servo in figure 1-1 is to position a load. The load may be a director, a radar antenna, a computing device, or a hydraulic valve. The load is attached in some manner to the output of the servo. Consider a director. Its position is controlled with train and elevation orders that are inputs to the servo.

A SERVO IS A POWER AMPLIFIER. The input to a servo is usually a very small signal. It is too weak to move the load by itself, so some sort of power amplification must take place within the servo. Again, take as an example a servo used to position a director. To develop enough power to move the great weight of a director requires currents in the amperage range. Therefore, most servos you will work with have one or more amplifying stages. The amplifier may be electrical, electronic, hydraulic, or two or more of these in combination.

A SERVO IS A CLOSED-LOOP SYSTEM. Look again at figure 1-1. You can see that the response line runs from the output to the error detector. This response is a communication channel that reports the speed or position of the output back to the error detector. To see how response works, assume that the input is a mechanical signal telling the output to move to a certain position. The response signal reports the position of the output to the error detector. The error detector performs a simple mathematical operation. It subtracts the output from the input to get the amount of difference or error. And the error, rather than the input quantity, is the actual input to the amplifier.

Note that when the response equals the input, the error signal is zero. But whenever the response differs from the input, an error signal is developed. The error signal drives the output in such a manner as to reduce the error signal.

Keep in mind that response can be transmitted electrically, hydraulically, or mechanically in a servo.

A SERVO IS AN ENTIRE SYSTEM. It cannot consist of a single component. It must have the minimum number of components we have shown in the diagram of figure 1-1. There is no law against a servo having more sections than the ones we have shown. And they usually do. But regardless of the number of parts in a servo, they all work together as a system or team. This system concept is important. A servo is not an isolated motor or power amplifier, but must be considered as an entire system of interconnected components. Together, these components measure, transmit, compare, amplify, and control quantities.

### Functional Sections of a Servo

Figure 1-2 is a three-unit diagram of the elementary servo shown in figure 1-1. Each unit has a label that describes its function.

Our new diagram differs from the first one in that the power amplifier has been divided into two parts: an AMPLIFIER and an ERROR REDUCER. The amplifier increases the weak error signal, and it controls the error reducer. We have coined the term *error reducer* because the name closely describes the function of this servo section, which is to drive the output of the servo until it is equal to the input, thus reducing the error nearly to zero. Keep in mind that there can never be zero error. The error reducer must receive an error signal before it can control the output. The error signal, however, should be kept as small as possible.

In the servo shown in figure 1-2, the input, output, and response devices are mechanical shafting; the error detector is an electromechanical device; the amplifier is electronic; and the error reducer is an electromechanical unit.

Earlier, we described a servo as any device that uses the response to cancel the input signal. It can also be defined as a mechanism whose output tries to reproduce its input. Let's look at how the servo diagramed in figure 1-2 works, based on this point of view. Assume that the input and the output shafts are at the same position. There is no error between them, and so there will be no error signal to the amplifier. Therefore, the error reducer will not receive a correcting signal, and the servo will not move. But if the input shaft is suddenly turned to a new position, there will be an instantaneous angular difference between the positions of the input and output shafts.

Where is this difference detected and measured? The answer is, of course, at the error detector. The input and response shafts are both inputs to the error detecting device, which, as we said before, is electromechanical. Since the response shaft is geared to the output shaft, the

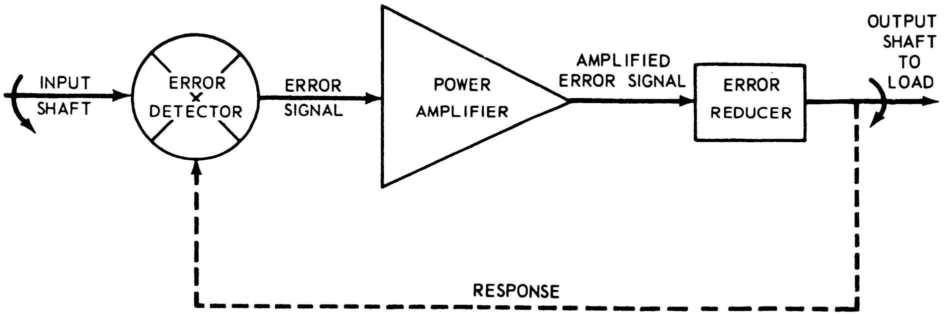

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Figure 1-2.—Three-unit diagram of an elementary servo.

response duplicates any position and motion of the output. In other words, knowledge of what the output shaft is doing is fed back over the response line to the error detector. Here, the positions of the input shaft and output shaft are compared. The error detector measures any difference between them, and then it does something more. It changes mechanical position error into an electrical error signal. The electrical error output of the error detector is directly proportional to the angular difference between the input and output shafts.

The electrical error signal is relatively weak. So, it must be amplified. After it is amplified, it is sent to the error reducer. Here, the error signal is changed from its electrical form to a proportional mechanical signal. Now, the error reducer drives the output shaft in a direction that reduces the error between the output and input shafts. As the output shaft turns, so does the response line, but it turns in a direction that reduces the difference between the input and response signals. When the output and input shafts are in agreement, the output of the error detector is zero. The amplifier sees no signal at its input, and the servo stops.

Now, if we turn the input shaft at a constant velocity, the output shaft should turn to the same position as the input shaft and follow it at the same speed and in the same direction. If the input shaft were to speed up, then reverse its direction, the output shaft should faithfully reproduce these mechanical gymnastics—and all the while, the two shafts should remain closely aligned. If at any time they do not, then the error detector will produce an error signal. This signal is amplified and sent to the error reducer. It then drives the output shaft until the error between the input and output is as nearly zero as possible. When this condition exists, the servo is said to be *nulled*. Other terms that describe zero or nearly zero error are synchronized, in synchronism, and in correspondence.

In the preceding pages of this chapter, we have given you a general idea of the functional sections of a servo and what they do. You learned that the input is the controlling quantity. We described it as the displacement of a shaft. In practical servos or power drives the input is generally an electrical quantity that represents a shaft position. The *servo error* is the difference between the input and output of the servo. The error detector is the device that compares the input with the servo output. The error reducer is essentially the prime mover of the servo. It is controlled by the amplifier section, which simply increases the strength of the error signal so that it can move the error reducer. We mentioned the load earlier. While the load, strictly speaking, is not a component of the servo, load characteristics (size, weight, etc.) have an important bearing on the design and operation of the servo.

### Signal Types

A servo's output is an accurate duplication, with an increase in power, of the input order signal. The *order signal* represents the desired action, and, therefore, determines the servo's response. The order can be a position, a velocity, or an acceleration signal. Let's consider the three types of order signals. Position is a relative quantity that indicates a place or point in a scale of measure or reference frame. Hence, position is a scalar quantity and it has no further meaning. Movement from a position results in a displacement. Displacement is a vector quantity having both magnitude and direction. If we time a displacement, we can obtain a velocity. *Velocity* is a time displacement; that is, the rate of change of position. Velocity then is a vector quantity being derived from displacement, also a vector quantity. (Incidentally, speed is a scalar quantity having only magnitude.) A change in velocity is an acceleration. Hence *acceleration* is a vector quantity. Strictly speaking, an acceleration is a change in velocity and therefore can be either an increase or decrease in speed or a change in the direction of motion.

Scalar quantities can be combined by simple arithmetic. Vector quantities, however, are more difficult to combine. Since both direction and magnitude are involved, vector addition is required. It is the job of the error detector in a servo to combine the input and response signals whether they are vector or scalar quantities. Vector quantities can be combined by simple arithmetic if their directions are along a common axis. In servos the output is a duplication of the input and therefore their directions must be common.

Often, order signals must be converted from one type to another. For example, the fire control radar will measure the displacement of a target from the line of sight. From this displacement a velocity is derived to change the rate of motion of the director. On the other hand, we may have a computed rate of motion and require measurement of the displacement that will occur during a given amount of time. We can change the signal because displacement, velocity, and acceleration are functions of each other, and each is a derivative of the other. A derivative is a quantity that is obtained from another. If we know that a displacement occurred in a measured interval of time, we can derive the rate of motion. And it follows that if we know the rate of motion, we can derive the displacement that will occur during an interval of time. These signals are obtained in servos by integration. We will not go into integration here since it can be reasoned that if one of the quantities and time is known, the other quantities can be derived.

## CONTROL SYSTEM TERMINOLOGY AND SYMBOLS

Fundamental to understanding the control system in any depth is a familiarity with terminology, definitions, and symbols used to describe a system and its characteristics. The subject is often misunderstood or thought of as complex because the representative terms are not understood.

Control systems simply combine known principles, and some way of describing their characteristics is essential, resulting in the new terminology. The symbols are simple shorthand, or a way of abbreviating the terminology.

Because of the rapid advancement of control systems in recent years, a completely common language has not yet evolved. This has, in part, led to the belief that the subject is complex. Remember that the principles never change; only the techniques and methods of description change. If the underlying principles are understood, then the control systems will be understood.

### Schematic and Block Diagrams

Examination of an actual physical control system does not explain the functional operation or show all of the physical details. Nevertheless, this type of information is shown on one of two distinct types of drawings: (1) the schematic and (2) the block diagram.

A *schematic diagram* illustrates a system by showing physical connections between component symbols. A schematic does not show the flow of information, the function of a circuit, or the function of individual components. Schematic diagrams are used in the assembly, installation, maintenance, and troubleshooting of electronic circuits. One-function prints, each covering the components and connections for only a single quantity (such as, gun or missile orders, director train, range, etc.) of a system, have been developed to simplify troubleshooting of highly complex fire control systems.

On the other hand, a *block diagram* shows the elements of functional interest and the flow of information, but it disregards the physical aspects shown in a schematic.

The two types of motors (fig. 1-3) differ physically but perform the same end function.

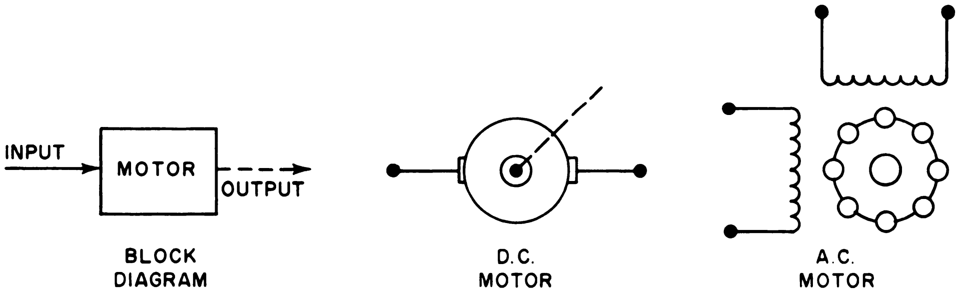

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Figure 1-3.—Block diagram and schematic symbols of motors.

Therefore, the block diagram can represent either motor since it is concerned with functional elements of interest. The arrowed lines denote the direction of information flow and should be labeled to indicate the element of interest.

The output element of interest could be shaft position or velocity, depending on its functional application. If the output of interest were velocity, the block diagram output would be so labeled and the input element of interest would be labeled as voltage, since a motor's velocity depends on voltage. Alternatively, if the output of interest were position, which is a component of torque, the output would be labeled position and the input labeled current, since a motor's torque depends on the amount of current present.

The block diagram can be used to represent any component or group of components. For example, a single block can represent a complete amplifier, with the input and output elements of interest labeled. A block can represent a hydraulic piston, in which case the input element of interest might be fluid pressure and the output element of interest output force displacement. The arrows point the direction of information flow, regardless of actual direction of current or fluid motion.

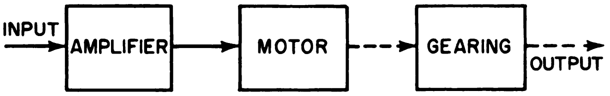

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**Figure 1-4.—Block diagram of open loop control systems.**

It should also be appreciated that the element of interest is not the only element going in or out of the block. If current is present, there must be a voltage causing the current, but only the element of interest is labeled.

When various component blocks are connected to form a system, the output of one becomes the input to the next. Figure 1-4, in block diagram form, shows an open loop control system.

The block diagram of figure 1-5 shows five important control engineering symbols and has a new block added entitled "response transducer." The term *transducer* is generally defined as a device that converts one form of energy to another. In the control system context it represents the components that measure the controlled element of interest. Its input is converted to a compatible signal and is fed back to a point where it is summed with the input signal to generate the system error signal. It is the accepted term for the response components in block diagrams, since the block diagram shows only signal information and functional elements of interest. The specific response components will vary with the type of systems that are specified only in the schematic diagram.

### Symbols and Definitions

The control engineering symbols are as follows:

- The Greek letter *sigma*, meaning summation, surrounded by a circle. This is the summation, or "sum point," where the reference and

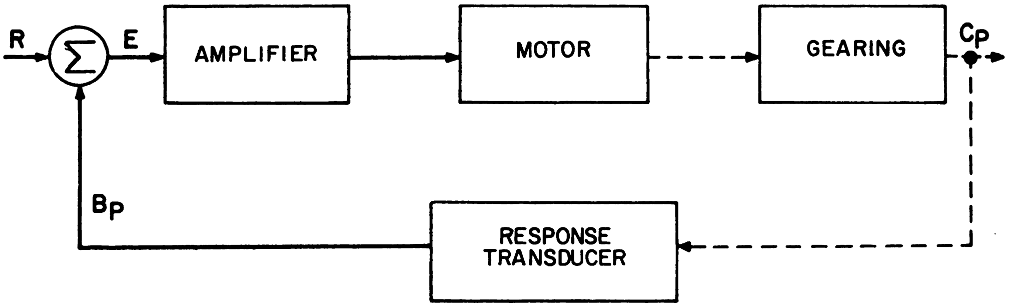

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**Figure 1-5.—Block diagram of position servo systems.**

response signals are summed to derive the error signal that controls any servo.

- The letter R stands for the "sum point input reference signal." The reference signal may directly be the input signal, but in some instances the input signal may be changed before reaching the sum point to make it compatible with the feedback signal.

- The letter B is the symbol for the "response signal"; the sub p with this symbol identifies signal content as being position related.

- The letter C is the symbol for "output variable" and the sub p indicates that the variable of interest is position.

- The letter E is the symbol for the "error signal."

The symbols can be enlarged with additional sub letters to give further information, as in the case of R, $B_p$, and E, to show they are either voltage or current.

### System Type Identification

A servo system, by convention, is identified by its prime mover, which is a control system term for the component that does the actual work. For example, electrical motors and hydraulic and pneumatic pistons are prime movers. A servo system that employs a dc or an ac motor is called a dc or an ac servo.

One employing a pneumatic or hydraulic piston is called a pneumatic or hydraulic servo. With the advent of combination systems such as a dc motor being controlled by ac components and signals or a hydraulic system controlled by dc components and signals, the conventional identification is often confusing. Both the prime mover and method of control should be identified whenever they differ. The case cited above of a dc motor being controlled by ac components and signals should be described as an ac control dc motor servo system in lieu of describing it as a dc servo system.

All types and classes of servos employ the same basic servo theory and have similar dynamic operating characteristics. The ac servo, so called because it employs ac components and signal information, was the first widely applied servo. It came into wide use in military applications during the latter part of World War II.

No one type of servo can meet all requirements so other types of systems and components were developed, leading to dc, hydraulic, and pneumatic servo systems. Electric servos account for the majority of application; however, all types are in widespread use.

Ac servo components operate on more complex electromagnetic principles and are controlled by ac modulated signals that tend to obscure the real servo principles. The dc servo in certain respects is comparable with hydraulic and pneumatic servos that often employ dc control techniques and components. It makes a good example system for a student of basic servo theory because all of its signals, including the all-important error signal generation, are around zero frequency. When dealing with dc or near zero frequencies, signals can be easily observed and measured with uncomplicated instrumentation.

## POWER SYSTEMS

The input signal to a servo is weak, and a large boost in power is needed before the servo can do its job. The type of power used in a servo is determined by its job. Electric servo systems are used with light loads. But if the load is large and variable, the servo must have an amplifier to increase the signal power supplied the error reducer. Most servos in fire control equipment are electromechanical; the amplifier is electronic, and an electric motor is used as an error reducer. There are, however, a few electrohydraulic servos in fire control. In the hydraulic servos, the input signal is amplified in an electronic amplifier. The amplified signal controls an electric device, which, in turn, controls the hydraulic power system.

Each type of power has advantages. The electric servo is the simplest. An electronic amplifier is flexible and can adapt the servo to the load. Thus, the electronic system provides positive control at variable speeds. Hydraulic systems cannot be backed down by the load. Therefore, they are used with heavy loads subject to sudden and drastic changes. Radar antennas that have a large area exposed to the effects of wind force are examples of this type of load.

## ELECTRIC SERVO

In an electric servo, a bearing-mounted synchro operates a set of contacts that control the supply voltage to a servomotor. The motor drives when the synchro closes the contacts. The response from the motor drives the synchro in the opposite direction from the synchro's signal and opens the contacts. Thus, the servo operates until the synchro signal is reduced to zero. Figure 1-6 shows a bearing-mounted synchro and figure 1-7 shows the electrical arrangement of the servo. The servomotor is a 115-V ac motor with split phase operation. The capacitor in the circuit shifts the phase of the voltage to one of the motor's windings. The contacts determine which winding will receive the shifted voltage, and hence which way the motor will drive. One side of the line voltage is connected to the common point between the stator windings of the motor. The other side of the supply is connected to the center contact, which is connected to the rotor of the synchro. A signal to the synchro causes the center contact to rotate and complete the circuit to either the left- or right-hand outer contact. Note that either of the outer contacts will complete the circuit to the motor, but by separate paths. The capacitor will be in series with only one of the motor's windings. The capacitor shifts the phase relationship of the voltage applied to the other windings. The motor will drive until the response opens the contacts.

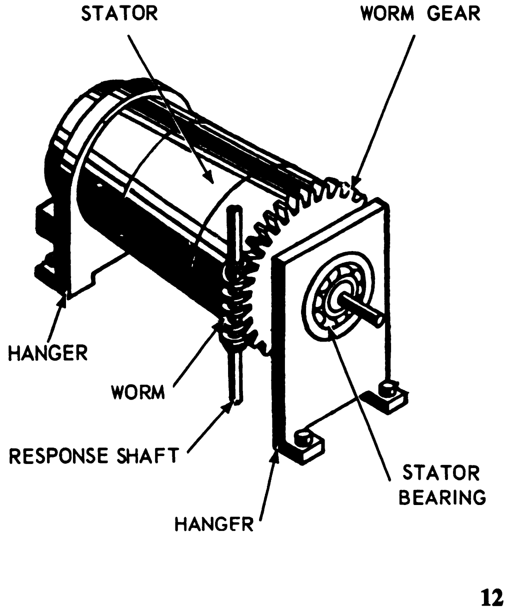

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Figure 1-6.—Bearing-mounted synchro receiver.

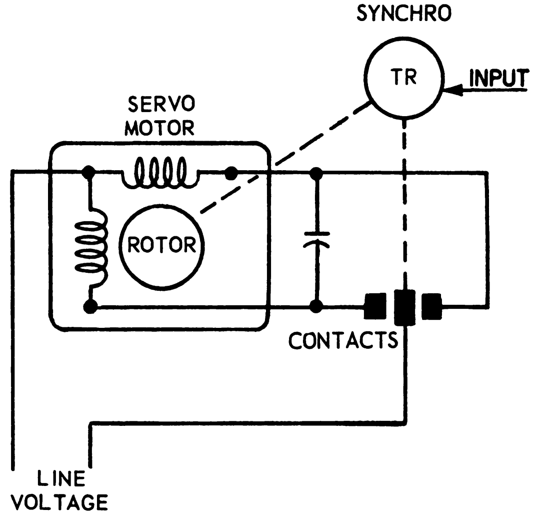

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Figure 1-7.—Electrical servo.

The advantage of electric servos is their simplicity. Their disadvantages are (1) the lack of speed control and (2) their limited current-carrying capacity. The servo is either synchronized or driving, and thus is strictly a position control. The low torque of the synchro limits the size of the contacts and hence their current-carrying capacity. This, in turn, limits this type of servo to light loads.

## ELECTROMECHANICAL SERVO

The servo system represented in figure 1-8 is an example of an electromechanical servo. This particular servo employs a synchro transmission system for the transmission of radar range information from a fire control radar range unit to a computer range servo.

Assume that the fire control radar has measured target range at 10,000 yards. The CX

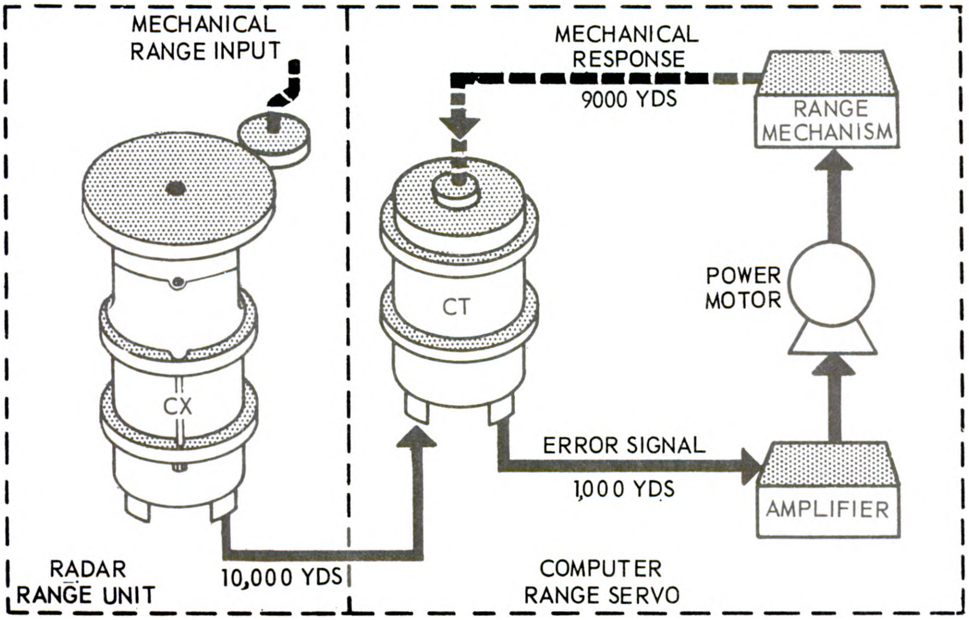

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Figure 1-8.—Position servo.

in the radar (fig. 1-8) will transmit range to the CT in the computer. Assume that the range servo in the computer is at 9,000 yards. Hence, the CT, the error detector, will not be at its null position. The error signal from the CT will be proportional to the 1,000 yards displacement between the ordered position and the actual position of range in the computer. The servo will drive until response positions the rotor of the CT at its null position, which represent 10,000 yards range.

The electromechanical servo just presented is one example of an electromechanical servo. Other devices such as potentiometers, gyros, and resolvers also can cause a servo to be classified as electromechanical.

To this point we have not said much concerning servo amplifiers. Obviously the primary function of the amplifier is to increase the strength of the error signal. But an amplifier has many features that can be used to improve the servo's operation. Many types of amplifiers are used in servos. Therefore, it is not practical to discuss individual amplifiers at this time. We will discuss some of the advantages of having an amplifier in a servo.

An amplifier can increase the signal power to a practical level. The amplifier may be made sensitive to signals with a certain frequency, amplitude, type of voltage, and phase or polarity. The amplifier isolates the signal source from the load. The error signal feeds into the fairly constant impedance of the amplifier's input circuit and not into the variable inpedance of the load. At the same time, however, the amplifier's gain can be varied by feedback signals to automatically adjust the amplifier's output to compensate for the condition of the load.

The theory of operation of electromechanical servos is identical to that of all closed-loop servos. Response from the output is fed back to the input to null the error signal. The amplifier has a large power source, which is controlled by the low-powered error signal. The amplifier can detect the direction in which the load must be moved by the phase or polarity of the error signal. The amplitude of the error signal determines the amount or the velocity of the servo's output.

## ELECTROHYDRAULIC SERVO

Hydraulic components used in servomechanisms are frequently found in weapons systems.

Hydraulic power devices, such as motors and associated control valves, have an advantage of a much faster response than the best electric motors and equal to that of a magnetic clutch system. They also require a minimum of maintenance, have very high accuracy, and are well adapted to heavy loads.

The essential components of a hydraulic system are as follows:

- A source of high pressure oil and a sump to receive discharge oil
- A control valve and a means of employing an actuating signal
- An actuator (motor or cylinder)

**Hydraulic Transmission Assembly**

The hydraulic transmission assembly (fig. 1-9) consists of a variable displacement pump (A-end) and controls and two fixed displacement motors (B-ends). The variable displacement pump is driven at a constant speed by an electric motor. The fluid flow from the A-end pump to the B-end motors is governed in volume and direction by the position of the A-end yoke, which responds to the train error signal from the train servo amplifier. The B-end motors are connected through drive-left and drive-right train gearboxes to the train bull gear.

The A-end is driven by the electric motor to provide the varying nonpulsating flow of hydraulic fluid that is required by the system to control the position of the load (radar antenna or director). This flow of hydraulic fluid under pressure is used to actuate the two B-ends.

The B-end motors are employed in the hydraulic transmission to convert hydraulic energy to mechanical energy. The drive shafts of the B-ends are connected to a gearbox containing gears that mesh with the director's gearing (bull gear).

The two B-end motors, connected hydraulically in series, are used to drive the train member. High-pressure fluid is applied to only one of the B-ends at a time, depending upon which direction the train member is to rotate. The other B-end is then driven by the train bull gear and functions effectively as a low-pressure pump. Hydraulic pressure is maintained on each B-end inlet by the replenishing pump. This pressure causes both motors to try and rotate, but in opposite directions. The torque from the motors is equal but opposing; therefore, no rotation takes place. The opposing torque keeps the gears meshed and prevents backlash. The replenishing pump also replaces fluid that is lost in the high-pressure circuit by leakage and thus prevents cavitation.

The operation of a hydraulic motor can be considered as exactly opposite to the operation of a hydraulic pump. A pump is driven by mechanical means and produces flow. The motor is driven by fluid flow, the energy of which is transformed in rotary mechanical motion.

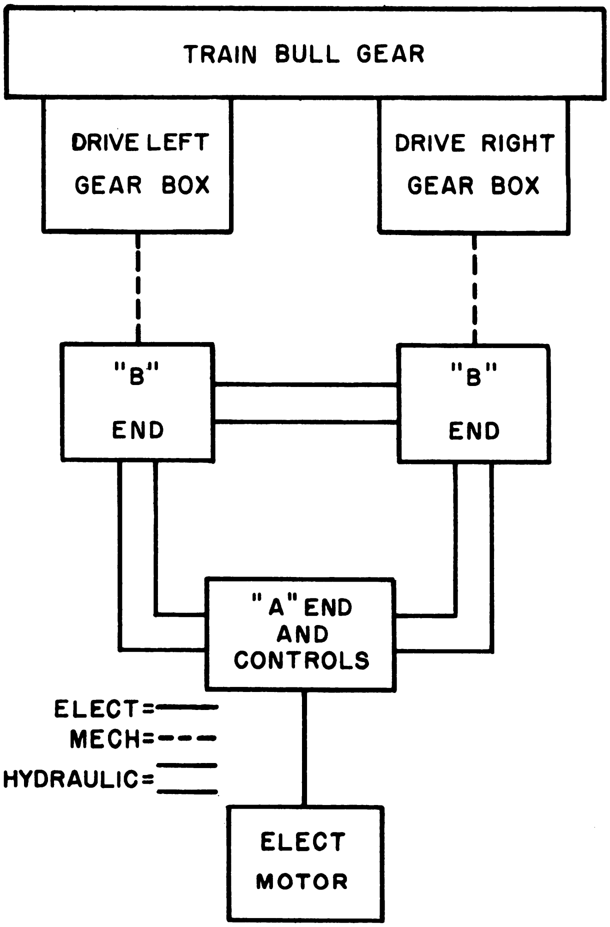

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Figure 1-9.—Simplified hydraulic transmission system.

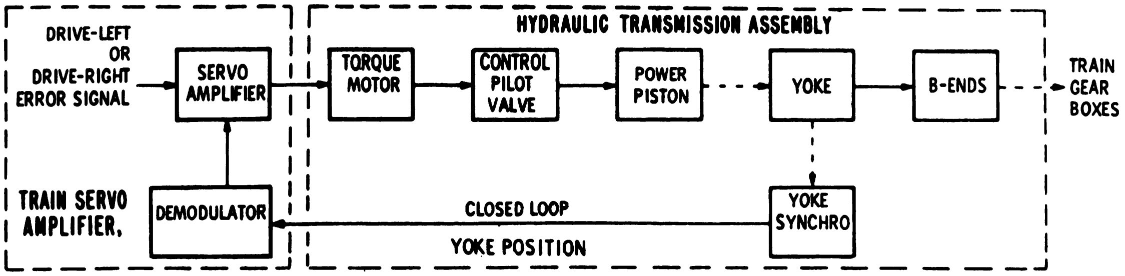

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Figure 1-10.—Train servo control loop, block diagram.

## Servo Control Loop

The control of the hydraulic transmission assembly is provided by a closed servo loop (fig. 1-10), which consists of the train servo amplifier, torque motor, control pilot valve, power piston, A-end yoke, and yoke synchro transmitter. The train servo amplifier supplies a directional drive signal to the torque motor, which, in turn, controls the operation of the control pilot valve. The control pilot valve then operates the power piston that is connected to the swivel yoke in the A-end. Since the angle of the yoke determines the direction and velocity of train rotation, the synchro transmitter, connected to the yoke, provides a yoke position (train velocity) feedback signal to the amplifier through a demodulator in the train servo amplifier, thus completing the control servo loop.

When the train member is to be rotated, either a drive-left or a drive-right signal from train servo amplifier is applied to the control windings in the torque motor (fig. 1-11). This error signal introduces an unbalance between the currents in the two windings. These currents create an unbalance in the magnetic forces in the windings that is proportional to the error signal. These forces position the armature accordingly. The armature, mechanically linked to the control pilot valve, moves in the direction required to produce an acceleration in train until the yoke reaches the required position. When this point is reached, the feedback signal applied to train servo amplifier from the yoke synchro nulls the drive signal to the torque motor. The armature of the torque motor is pivoted on torsional springs that tend to return it to its neutral position when the unbalancing currents are removed from the solenoid windings. A pin is attached at the extremity of the armature. This pin enables the yoke power limiter feedback fork in the power mechanism to impart motion to the armature of the torque motor.

The control pilot valve determines whether the large area of the power piston receives control pressure or sump pressure. In its neutral position, this control pilot valve blocks off both these supplies to the large area of the power piston.

The power piston is connected directly to the A-end yoke through a pin and link. Any movement of the power piston from its neutral position swivels the yoke and thus initiates pumping action by the A-end pump. The power piston operates on a differential pressure principle. The control-pressure fluid acts against the lower side of the piston on an area that is half that of the upper side. When the upper side also receives the control-pressure fluid, an unbalanced force results and the piston is driven downward. When the upper side is connected to the sump, the piston moves upward. When the control pilot valve is at its neutral position, the fluid, in the large area side of the power piston and in the connecting line to the control pilot valve, remains at the pressure established before the valve assumed its neutral position. Thus, the power piston is maintained at a fixed position. In addition, the amount of fluid the control pilot valve allows to enter the power piston determines the distance that the piston is displaced.

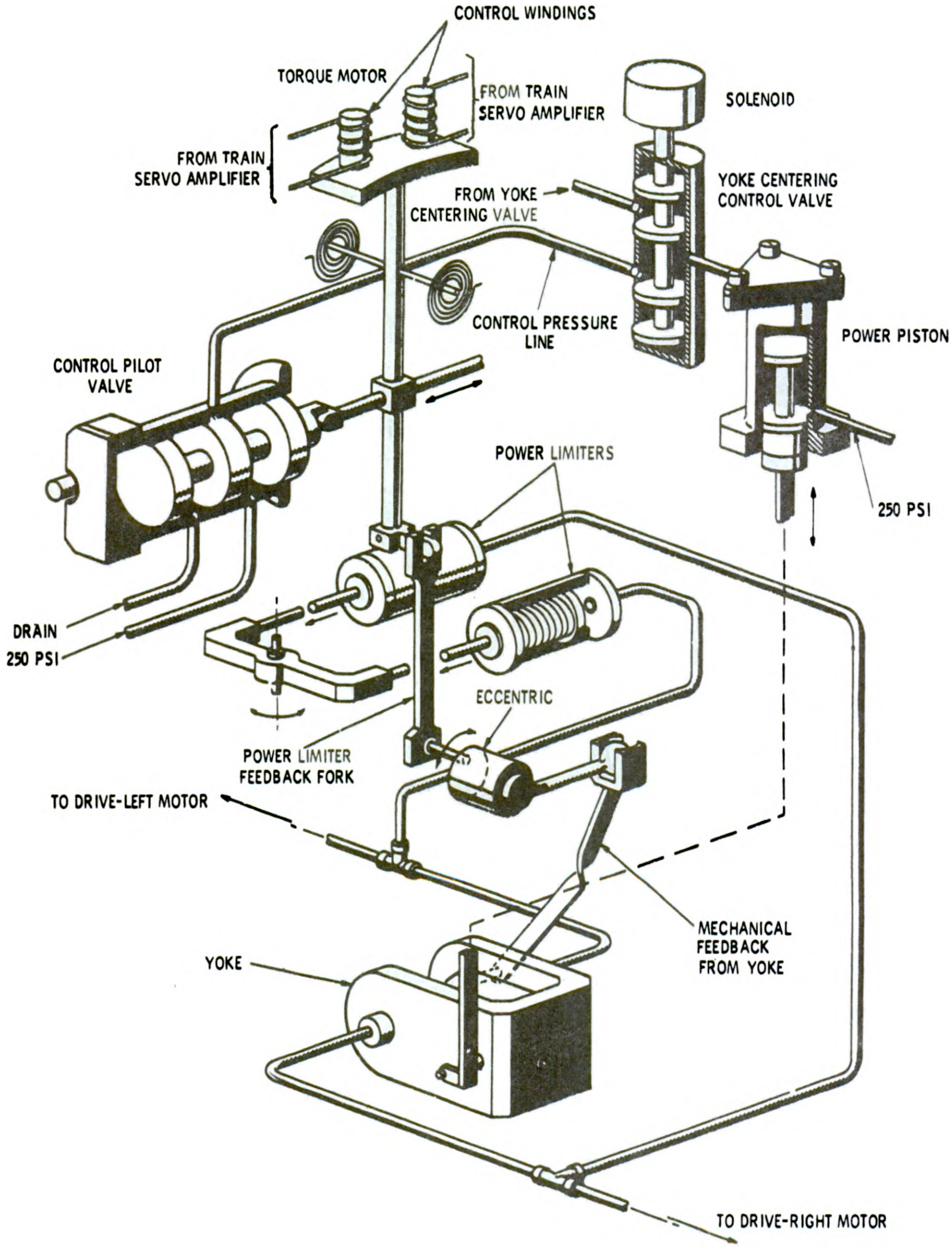

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Figure 1-11.—Train servo control loop, mechanical diagram.

A synchro transmitter, geared to the yoke, is employed in the hydraulic transmission assembly to complete the control servo loop. This synchro transmits a signal proportional to the yoke position to the train servo amplifier. Attached to the shaft of the synchro is a split spring-loaded sector gear that meshes with a sector gear pinned to the end of the yoke. Rotation of the yoke imparts motion to the synchro rotor, registering the yoke position. When the torque motor windings are unbalanced by an error signal, the control pilot valve is moved off neutral by the torque motor. This movement causes fluid to flow into the power piston, which, in turn, causes the power piston, and therefore the yoke, to attain a velocity proportional to the flow of fluid. When the yoke reaches an angular position equivalent to the original torque motor error signal, the control pilot valve is returned to its neutral position. This repositioning action occurs because the synchro positional feedback signal is equal to 180 degrees out of phase with the original error signal and thus cancels the error signal. As the train member is positioned according to the original error signal, the error is reduced to zero. The signal from the yoke synchro then becomes larger than the position error signal, causing the control pilot valve and power piston to return the yoke toward its neutral position.

The sump pressure, previously mentioned, is produced by a replenishing pump that maintains the closed circuit of the hydraulic transmission lines at a specified pressure to compensate for the internal leakage of both the A-end and the B-ends and to prevent backlash.

## SERVO OPERATION

Three types of servo operation will be covered in this section: position, velocity, and acceleration. Operational characteristics of servos and the electronic circuits that make up servo devices will also be covered.

## POSITION SERVO OPERATION

The *position servo* is one whose end function is to control the position of the load it is driving. It can be used to position an infinite number of devices; for example, valves, control surfaces, platforms, and so forth. The input signal can be a manual input (i.e., in many remote control applications) or from a programmed tape, computer, or other source.

The input signal to a servo is outside the servo loop and is not part of the closed loop servo system. The input signal is essential to the servo's operation and must be made compatible with the servo's method of mechanization. In this example, a potentiometer is used to generate the input signal and is shown in both the system block diagram and schematic representations.

Figure 1-12 is a block diagram model of a dc position servo. A new block has been added with the letter "A," the symbol for the reference signal transducer. The input is "V," the symbol for input signal variable and its output symbol is R (the sum point input reference signal to the servo). As stated above, a command potentiometer is employed to generate the input signal, the input signal variable (V) is the shaft angle or position of the wiper arm. The amplifier, motor, and gearing blocks are designated $G_1$, $G_2$, and $G_3$. The letter G is the symbol for the gain blocks, which are numbered in the example because there are more than one. The response

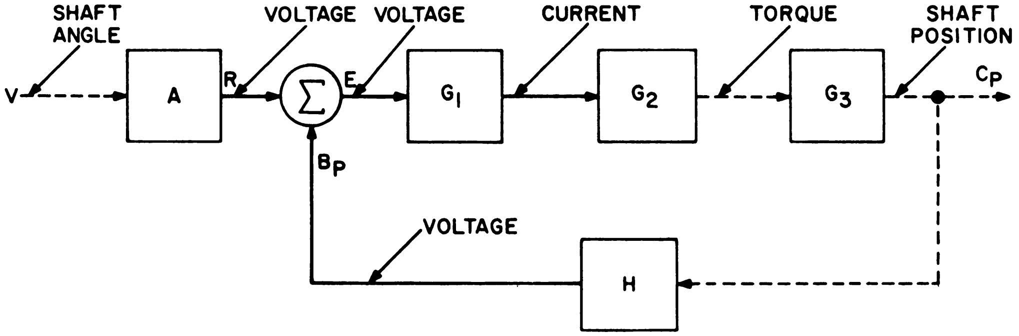

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Figure 1-12.—Block diagram of position servo.

transducer block is designated H (the symbol for feedback blocks). $C_p$ and $B_p$ represent the output variable and response signal, with the sub p again meaning position related. E, of course, represents the error signal and sigma symbolizes the sum point.

Note that only $G_1$ (the amplifier) has power gain or a higher energy output than the "E" input. The $G_2$ block (motor) changes electrical energy to shaft velocity or torque and has an energy loss. The $G_3$ block (gearing) is a mechanical transformer and also has an energy loss due to friction.

Therefore, the system can be broken down into three distinct sections. They are (1) the amplifier or power gain section, (2) the combined motor and gearing, called the actuator, and (3) the combination of input reference transducers, sum point and feedback transducers, called the error signal generation section.

Assume that $G_2$ is a 12-volt permanent magnet dc motor. The direction of rotation is determined by the polarity of the applied voltage. The polarity in one instance will cause clockwise shaft rotation and when reversed, will cause counterclockwise shaft rotation.

Figure 1-13 is a hybrid illustration, showing the gain elements as block diagrams and the error section in schematic form to help explain the system's operation. Certain points in the schematic portion are numbered and the signal common and the sum point identified only for explanation reference points. The schematic shows two 45-volt batteries as the reference power supply. $P_c$ is a manual command potentiometer whose knob positions the wiper arm, and $R_{cp}$ is a one-megohm summing resistor. These two components are the input variable signal transducers that are represented by the "A" block in the preceding diagram. $P_f$ is another potentiometer whose wiper arm is mechanically connected to the gearing shaft output (denoted by the dotted line) and $R_{fp}$ another one megohm resistor. These two components are the response signal transducers that are represented by the "H" block in the preceding diagram.

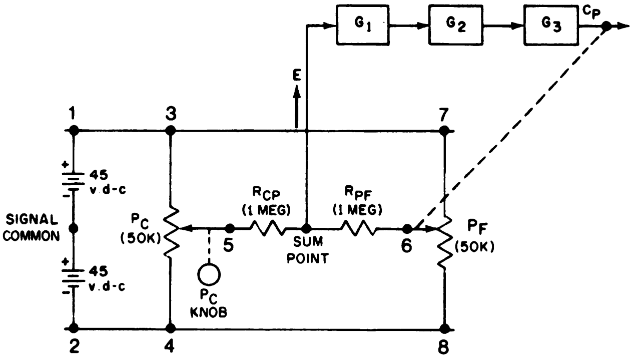

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**Figure 1-13.—Position servo showing "A" and "H" blocks in schematic form.**

Now assume the "G" blocks are properly mechanized for operation and the system is still motionless. Why? As movement or positioning depends upon an error signal having a value other than zero. If the error signal is zero, the system is in a steady state of equilibrium, or null position. With the wiper arms of $P_c$ and $P_f$ at the mid point of travel, a voltage measurement from signal common to point 5 or 6 is zero. Therefore, zero volts are also measured at the sum point, which means the value of (E) is zero. With no input signal, the amplifier output is zero. With no amplifier output, the motor is standing still.

Assume for a moment that the line between $G_1$ and $G_2$ is open, so the motor will not operate in any event. Now, imagine the $P_c$ wiper arm is manually moved upward to a new position where a voltage measurement from a signal common to point 5 would measure +10 volts. Further measurements would show zero volts between signal common and point 6, but +5 volts between signal common and the sum point. This +5 volts is "E", the error signal, and it would be amplified and drive the motor clockwise if the $G_1$—$G_2$ line were closed. Before closing the G line, first examine how the error voltage is developed. The +10 volts, measured at point (5), was achieved because the $P_c$ wiper arm was moved up 10 volts from signal common. Moving over to the sum point, 5 volts is measured; and at point 6, zero volts. The drop in voltage is due to the IR drop across the summing resistors $R_{cp}$ and $R_{fp}$.

---

Applying Ohm's law, solve for the IR voltage drop across $R_{cp}$.

First, the current in the circuit must be determined. Trace the current path from point 2 across to point 8, up $P_f$ to the wiper arm point 6, across $R_{fp}$ to the sum point, across the $R_{cp}$ to the $P_c$ wiper arm point 5, up $P_c$ to the positive side of the line at point 3. Neglecting the resistance of $P_c$ and $P_f$, which are very small compared to the summing resistors, the circuit resistance is 2 megohms.

Therefore,

I = E/R or 10 volts/2 megohms

I = 5 microamperes

Second, now that the circuit current is known, the voltage drop across $R_{cp}$ can be determined.

E = I times R or 5 microamperes × 1 megohm

E = 5 volts drop across $R_{cp}$

Third, the drop across $R_{cp}$ and $R_{fp}$ can be determined.

E = I times R or 5 microamperes × 2 meghoms

E = 10 volts drop across $R_{cp}$ and $R_{fp}$

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Assuming the $G_1$—$G_2$ line is now closed, the instantaneous error signal input of +5 volts into $G_1$ is amplified, and the amplified output starts driving the motor and gearing. The output shaft will drive the load toward its new position.

Cancellation of an error signal by increasing the current flow through $R_{cp}$ and $R_{fp}$ is easily understood if you think of the circuit as being in a "null" condition (no error signal) when the sum point is 45 volts positive in respect to points 2, 4, and 8. This is actually the situation shown, and if you measured from points 2, 4, and 8 to either the signal common or sum point, you would read 45 volts positive.

When the output shaft turns, the $P_f$ wiper arm is turned by the mechanical coupling. As soon as the wiper arm is turned, the voltage it picks off begins decreasing. Thus, if the reference voltage (signal common) is considered as being 45 volts positive in respect to point 2, the $P_f$ wiper (point 6) is moved in a negative direction, or toward point 8, and measures 40 volts positive in respect to points 2, 4, and 8. Therefore, the response signal ($B_p$) is negative with respect to the input signal (R). The proper polarity relation can be determined analytically if component data is available or by observing that the coupling drives the wiper arm of $P_f$ in the direction opposite the movement of the $P_c$ wiper arm.

With the voltage decreasing at the $P_f$ wiper arm (point 6), the +5 volts error signal decreases in value. To see this more clearly, suppose the voltage from signal common to point 6 is being measured. The voltage being measured is going negative. The input signal variable ($P_c$ wiper arm position) is not changing, so when the $P_f$ wiper is at +40 volts (in respect to point 8), the error signal is reduced as follows:

The voltage difference between points 5 and 6 is now 15 volts, so the current through $R_{cp}$ and $R_{fp}$ is

I = E/R or 15 volts/2 megohms

Therefore,

I = 7.5 microamperes

The IR voltage drop across $R_{cp}$ is

E = I times R or 7.5 microamperes × 1 megohm

E = 7.5 volts drop across $R_{cp}$ so the voltage at the sum point (error signal) is now 2.5 volts.

When the $P_f$ voltage reaches −10 volts, the error signal voltage will have been reduced to zero and the system then stops at its new position. This new position is the null position, which is descriptive of a servo being in a state of equilibrium, regardless of its position.

Error signal generation is the basic foundation of any servo system.

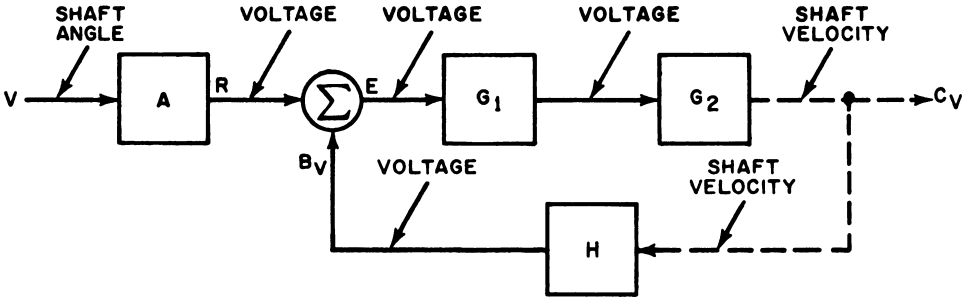

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Figure 1-14.—Block diagram of velocity servo.

## VELOCITY SERVO OPERATION

The velocity servo, while based on the same principle of error signal generation, differs from the position servo in operation in a number of ways. Two of the major differences are as follows:

- The output variable element of interest is velocity instead of position.
- In operation and null, an error signal is always present.

The velocity servo is used in applications where the controlled output variable drives a load device at a constant speed, which is established by the level of the error signal present. The types of load it can drive include radar antennas, shafts, star tracking telescopes, machine cutting tools, or any device requiring variable speed regulation.

Figure 1-14 is a block diagram of a velocity servo. Although similar to the position servo, the shaft output is noted sub v, indicating that velocity is the element of interest. Also, the response signal B is noted sub v, indicating it is a velocity related signal.

In figure 1-15, the gain blocks are shown in block diagram form and the error signal generating section is shown schematically. The power supply and reference points are shown for explanation purposes. The velocity servo employs the same reference transducers. The $P_c$ command potentiometer and $R_{cp}$ summing resistor are the same as were used in the position servo. However, the response transducers are changed to a tachometer (dc generator) and a 3 megohm summing resistor, $R_{fv}$. The tachometer shaft is mechanically coupled to the $G_2$ (motor) output. The tachometer generates a voltage proportional to speed, in this case, the transfer function is 1 volt/200 RPM. The polarity depends on the direction of shaft rotation.

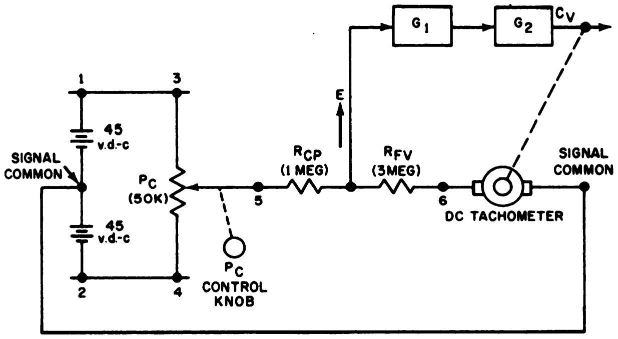

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Figure 1-15.—Velocity servo with "A" and "H" blocks in schematic form.

The "G" blocks are assumed properly mechanized and the motor is again a 12-volt dc permanent magnet motor. The combined transfer function of the $G_1$ and $G_2$ blocks will be assumed to be 1,000 RPM ($C_v$)/volt (E). The system is not operating because no input signal is present since the $P_c$ wiper arm is at zero volts (signal common to point 5) and the tachometer is not turning, so no error signal is present.

Now imagine, while measuring the voltage from signal common to point 5, that the $P_c$ wiper arm is manually moved downward until the voltage measurement is $-10$ volts. Instantaneously, the error signal becomes $-7.5$ volts. Why? The tachometer output was at zero, so the current (neglecting $P_c$ and the internal tachometer resistance) through the summing circuit is 2.5 microamperes (I = 10/4 megohms). Therefore, the drop across $R_{cp}$ is 2.5 volts (E = 2.5 microamperes × 1 megohm). The voltage at the sum point must then be $-7.5$ volts (measured from signal common across $R_{fv}$ and dc tachometer) and is the error signal (E).

With a $-7.5$ volt error signal as the input to $G_1$, the motor begins to turn counterclockwise. The transfer function between ($C_v$) and (E) was stated as 1,000 RPM/volt, which means the motor will accelerate to 7,500 RPM if (E) maintains this level. Nevertheless, the motor is coupled to the tachometer, so as soon as the motor starts turning, the tachometer begins to develop a voltage of the sign opposite the input. (The tachometer polarity was determined by the way the tachometer leads are connected in the error signal generation section.)

When the motor velocity and tachometer reaches 3,000 RPM, what is the error signal? It was stated before that tachometer develops 1 volt per 200 RPM, so the tach output at 3,000 RPM is +15 volts. The $P_c$ voltage is $-10$ volts. The comparator circuit current, again neglecting the relatively low $P_c$ and tachometer resistance, is 6.25 microamperes and the IR drop across $R_{cp}$ is 6.25 volts. The voltage at the sum point, which is the error signal (E), is now $-3.75$ volts. The motor is still increasing in speed but now towards a new target of 3,750 RPM.

When the motor speed reaches 3,333 RPM, the tach output is +16.66 volts. What is the error signal (E)? The circuit current is found to be 6.666 microamperes and the error signal is reduced to 3.33 volts. The motor speed is 1,000 RPM per volt of error signal, so unless the error signal increases, the motor can go no faster. The only way to increase the error signal would be to further increase the input variable signal, in which case the system would speed up to the new point of equilibrium between motor speed and error signal.

The equilibrium is the velocity null, and an error signal is always present but remains steady in the velocity null state. While the system is following a command to increase or decrease speed, the error signal (E) is changing in value.

## ACCELERATION SERVO OPERATION

The *acceleration servo* is based on the same basic principles as the position and velocity servos. Its output variable (C) is acceleration (rate of change of velocity) or ($C_a$). The response transducer that measures the controlled variable is an accelerometer, and the response signal $B_a$ is a signal related to the acceleration of the output.

The "accelerometer" may not be an accelerometer in the true sense of the word. To understand what we mean by this, consider, once again, the output of the tachometer in the velocity servo. The tach output changed from zero volts to +16.66 volts over a period of time. Therefore, the rate of change of the tach output is indicative of the acceleration. There are methods of both determining this rate of change and using it to affect the response so as to aid the acceleration of the output. In other words, the response signal will assist the input signal in overcoming the inertia of the load. As the output is accelerated to its new velocity, the effect on the response diminishes until once again a null or state of equilibrium exists between input signal and response. More will be said concerning this when we consider the operational characteristics of servo systems, which is the next subject of interest.

## OPERATIONAL CHARACTERISTICS

The operational characteristics of a servo are determined primarily by its job. There are just about as many different types of servos as there are jobs for servos to do. Generally speaking, a servo has a common purpose—to control its output in a manner dictated by its input. Ideally, the motion and position of the output shaft should duplicate the motion and position of the input shaft. But we never get ideal performance from servos. We will discuss the major reasons for this, and show some of the approaches taken to improve servo performance.

There is always a time lag between a change in the input signal and the servo's reaction to the change. Any physical motion requires time. In addition, the error signal must have sufficient magnitude to cause the servo to drive. Below this level the servo is insensitive to signal change. The servo's time lag will be decreased, and its sensitivity to small signal changes increased, by an increase in the gain of the amplifier. But if the gain is set too high, the servo output will tend to oscillate and be unstable. Hence, the gain of a servo is limited by stability considerations. The sensitivity of a servo is counterbalanced against its stability to obtain the best operation.

All signals in a servo, except for the response signal, are considered to originate outside the amplifier. Input signals to a servo always contain some roughness, such as noise in an electrical signal. This roughness must be eliminated to obtain smooth operation. Let's consider a director train power drive with a position signal from a CX – CT synchrosystem. There are physical limits to the rapidity of the director's movements. Slow variations in position must be accepted as possible director motion, but rapid fluctuations in the signal may be rejected as being impossible for the director to achieve. Thus by an examination of the signal's frequency spectrum, we can detect and eliminate known noise frequencies. Filters in the signal circuit can shunt noise frequencies away from the amplifier and allow only those frequencies that represent director motion to enter the amplifier.

If the capabilities of a servo's load are known, we can attenuate or eliminate some of the unwanted frequencies in the signal. In other words, a bandwidth for the servo amplifier is established. The bandwidth must include all the frequencies that could represent valid signals. Hence, frequencies that are actually caused by noise, but could represent valid motions of the signal, must be accepted. Damping and stability feedback are used to reduce this roughness in the servo. We will cover damping later in this chapter.

An increase in bandwidth causes a corresponding increase in noise generated in the amplifier and a loss in gain. The response signal fed back to the error detector is proportional to the amplifier's output and contains any noise generated there. Since response is 180° out of phase with the input signal, it is a negative feedback. Consequently the advantages of negative feedback are applicable to servos. One of these advantages is that nonlinear distortions and noises generated in the amplifier are reduced by response. This does not eliminate noise in the error signal input to the amplifier.

Response in a servo tends to make the overall gain of the amplifier independent of variations in load, supply voltages, and aging of the tubes. This gives the amplifier a constant gain factor and the servo a flat amplitude response curve. A constant gain factor will provide a linear relationship between the input and output signals of the amplifier throughout its operating limits. Therefore, an error signal of a given amplitude will produce an output signal with a definite amplitude. The amplifier's output is, of course, the control signal to the error reducer. Hence, if the error reducer has a linear relationship between control voltage and torque produced, the servo's response will be directly proportional to the error signal.

Variations in the gain of a servo are sometimes desirable to compensate for load variations. Consider the director train servo we spoke of before. The director has mass and therefore has inertia. Inertia is the property of a body that resists changes in motion. A change in motion is an acceleration, and a force is required to accomplish acceleration. Since the director has inertia, a larger force is necessary to start the director into motion or to accelerate the director's motion than the force required to maintain the director at a constant velocity.

Assume the director is tracking a target that causes the director to train at a constant velocity to the right. Now assume that the target changes course, requiring the director to reverse its direction and train to the left. To do this, the train servo must first stop the director's movement to the right. Since the director has inertia, there is a sudden increase in the load on the servo as it attempts to stop the director. The error signal to the servo amplifier does not reflect this increase in the load because of inertia. Hence, there is a time lag before the director is stopped and started to the left. The time lag can be reduced if the gain of the amplifier is varied to compensate for load variations.

The load's variation is due to acceleration. Thus, a signal proportional to a change in the load's velocity could be used to vary the amplifier's gain. The velocity feedback signal would originate at the load from a source such as a rate generator.

The amplifier's gain is sometimes varied by the amplitude of the error signal. When there is a large displacement between the load position and the ordered position, we would want the servo to accelerate rapidly to its maximum velocity and to maintain that velocity until the load is close to the ordered position. The error signal to the amplifier could be used to shift circuits in the amplifier to vary its gain. When the error signal's amplitude reached a preset level, it would automatically shift the gain.

## SERVO CIRCUITS

In this section we will discuss the circuits and the components that make up a servo. It is not practical to cover all their applications in fire control servos. Therefore, we have divided the circuits by their function and selected applications that will teach the different methods of accomplishing the function. We will not cover the material presented in the basic texts (*NEETS modules*). Therefore, it probably will be necessary for you to review the basic texts before you study the material presented here. We will cover the application of vacuum tubes, transistors, and magnetic circuits, plus the use of amplifiers, motors, and generators without discussing the theory of operation of these units. Most of the material necessary to understand servos is in the basic theory.

### SENSING ELEMENTS

These devices measure, convert, or sense the INPUT and OUTPUT of any servo and express them in suitable form. The more common types of these devices convert motion into corresponding electrical energy and are part of the class called transducers. This RTM will not attempt to put the units treated here into any rigid classification system. Instead, some of the more common terms used by manufacturers and the Navy to classify these devices are mentioned so that you can become familiar with a wide variety of nomenclature.

#### Potentiometers

In servos, the input information is usually in the form of a voltage or shaft position. The error signal to the servo amplifier is normally an electrical signal. The response may be a voltage or a mechanical quantity. You can see that some energy-converting device is required in almost any servo, as well as a device that measures position of the input and output. A potentiometer is one of the simplest means of accomplishing these functions. You have already studied potentiometers used as transducers when you studied the preceding sections of this chapter, which covered position and velocity servo operation.

#### Variable Transformers

A variable transformer is a device in which the magnetic coupling (primary and secondary) between a set of stator coils and a set of rotor poles (that may or may not be wound) can be varied by moving either the rotor shaft, the stator assembly, or both. Variable transformers, like the other devices mentioned here, may be classified by many different methods. A few of these are application, construction, principles of operation, and manufacturers' trade names.

These devices may be used in servo systems to perform many functions. They are used to transmit information between remote units of a system. Some examples of data transmission units are synchros, resolvers, E-transformers, and the microsyn.

### SYNCHRONIZING CIRCUITS

Use of a dual-speed synchro transmission system increases the accuracy of the servo. But a dual-speed synchro system introduces a problem. How can a servo amplifier tell when it is, or should be, receiving a fine or a coarse signal? Most synchro systems transmit at one or more of the following speeds: 1X, 2X, 18X, 36X, and 72X. A typical dual-speed synchro control system, such as for bearing data transmission, has a *coarse CT* (control transformer) at 1-speed, and a *fine CT* at 36-speed. In this system, response from the servo to the fine CT is driven at 36-speed and each rotation of the shaft represents 10 degrees. Therefore, if the error is large, the servo could synchronize at a false point. To prevent this, control of the servo must be shifted to the coarse CT when the servo is more than two or three degrees out of synchronization.

A synchronizing circuit is included in the servo to sense how far the load is from the ordered position and then to switch the appropriate signal into control. The signal selected by the circuit is the input to the amplifier. The selection is based on the size of the error signals the circuit receives. The coarse signal is the predominant factor in the selection, since it is a measure of the servo's output position throughout its limit of motion. The coarse signal drives the system into approximate synchronization, where the fine signal is shifted into control. The servo is normally controlled by the fine CT; the coarse CT has control only when the servo is far out of synchronism.

### Relay-Operated Synchronizing Circuit

The relay circuit (fig. 1-16) connects the fine or the coarse CT to the amplifier. One side of both error signals is connected to the fixed contacts of relay K1. The other side of each error signal is grounded and thus is common. The movable contact of K1 is spring loaded so that it normally makes connection with the fine signal contact. Therefore, when K1 is deenergized, the fine signal is passed to the amplifier. And conversely, when K1 is energized, the coarse signal has control. Hence, the coarse signal is used to control the dc supply to the coil of K1.

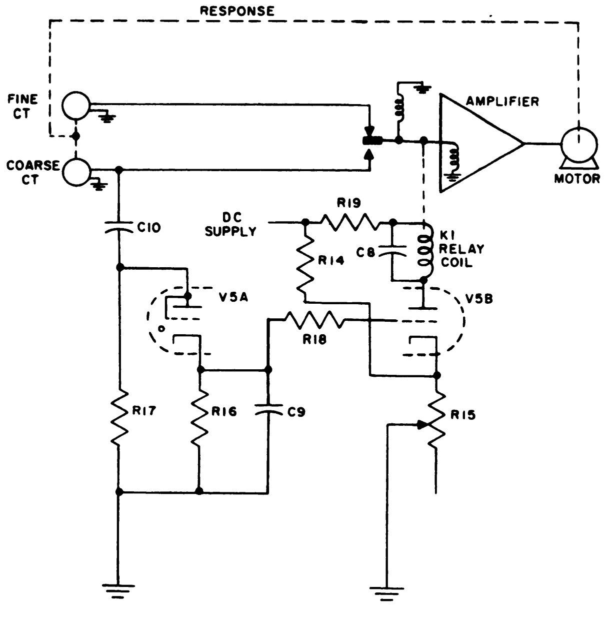

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Figure 1-16.—Relay operated synchronizing circuit.

The coarse signal is applied to the plate of V5A. The plate and grid of V5A are tied together and the tube operates as a diode, half-wave rectifier. When the plate is positive, it conducts. The output from V5A is a pulsating dc voltage taken from the top of R16, the cathode resistor. Thus, V5A rectifies the coarse signal.

Tube V5B is in series with the coil of K1. V5B is biased below cutoff by the cathode resistor, R15. The grid potential varies with magnitude of the rectified coarse signal from V5A. If the grid signal exceeds a fixed value, V5B conducts. When this occurs, current flows in the plate circuit and energizes K1. The relay will pick up and shift control to the coarse error signal.

The circuit for K1 is from ground through R15 and V5B, then through the coil of K1 and V5B, then through the coil of K1 and R19 to the positive side of the dc supply. Since the signal to the grid of V5B is a pulsating dc voltage, the tube's conduction will pulsate, which will cause the relay to chatter. C8 is placed across the coil of K1 to reduce the chatter of the relay. R19 is a voltage-dropping resistor in series with the relay coil. R14 and R15 form a voltage divider circuit. R15 is adjustable and controls the cathode bias of V5B.

R15 is adjusted so that V5B will conduct and K1 will pick up when the sign of the coarse error signal is the proper value. Normally, this will occur when the servo is from two to three degrees out of synchronism. The exact value of error signal will depend on the characteristics of the servo. Generally speaking, we want the fine CT in control of the servo as long as possible. For a small displacement, the fine error signal is much larger and provides a much tighter control of the servo. But if too large a coarse error signal is needed to pick up K1, we risk the possibility of a false synchronization or the

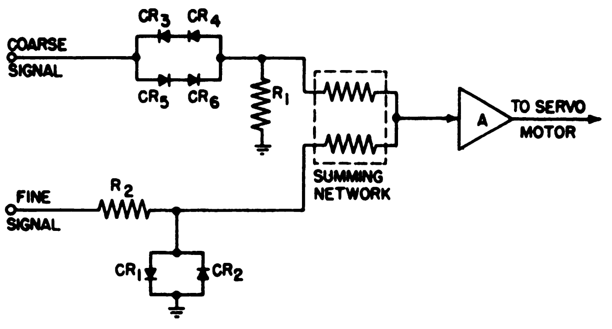

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**Figure 1-17.—Semiconductor diode synchronizing network.**

servo oscillating about the synchronization point as the fine and coarse CTs buck each other.

### Semiconductor Diode Synchronizing Network

The semiconductor diode synchronizing network is fairly common, so let's take a look at another circuit using this technique. This circuit is shown in figure 1-17. Within a range of approximately 3° on either side of the synchronizing point, the coarse signal is effectively blocked because of the high impedance of the series diodes, CR3, CR4, CR5, and CR6. With the coarse signal blocked, the fine signal is fed into the summing network and is in control of the servo. However, this signal is limited to a very low voltage by the parallel diodes CR1 and CR2.

Both the fine and coarse voltage inputs increase as the error in correspondence is increased. CR1 and CR2 develop the fine signal. A point will be reached (about 3° error) when CR1 and CR2 are incapable of dropping a greater voltage.

Now let us look at the coarse signal. In figure 1-17, you will notice that the coarse signal is developed across R1. Also notice that the diode network of CR3, CR4, CR5, and CR6 is in series with R1. Errors in correspondence that are less than 3° will cause some current to flow through R1 and the diode network. However, this current is small and will cause the diode network's resistance to be high. Therefore, most of the coarse signal voltage is dropped across the diode network and very little voltage is developed by R1. In this condition, the resultant voltage in the summing network is predominantly from the fine synchro. As we get further out of synchro correspondence, the current through the coarse signal diode will increase causing a decrease in the diode network's resistance. A smaller percentage of voltage will be dropped across the diode network, and thus more signal voltage developed across R1. Circuit resistance is selected so that the voltage developed across R1 (coarse signal) will override the voltage across CR1 and CR2 (fine signal) when the synchro correspondence error is 3° or more. The coarse signal now has control of the servo. When the servo error becomes less than 3°, the fine signal resumes control.

In similar circuits, zener diodes are used in place of the selenium or crystal rectifiers. When the voltage across a zener diode reaches the zener voltage (breakdown voltage), the current flow through the diode increases very rapidly while the voltage drop across the diode remains almost constant. (Zener diodes are covered in *NEETS Module 7.*) Therefore, when the coarse error signal is sufficiently large, the voltage will break down the zener diode's internal barrier. The large current flow means the signal will pass through the diode with a minimum of loss.

## MODULATORS

Some servos have a dc error voltage and an ac amplifier or motor. Consequently, the dc error voltage must be converted to an ac voltage that contains the same data, the direction and magnitude of the error, before it can be used. The circuit that converts the signal from dc to an ac voltage is called a modulator. Modulation is the process by which the amplitude, frequency, or phase of a carrier wave is varied with time in accordance with the wave form of a superimposed intelligence. Modulation and demodulation are covered in *NEETS Module 12.*

In the modulator circuit, the carrier wave is the servo's ac reference voltage. The superimposed intelligence is the dc error signal. The polarity of the dc error voltage indicates the direction of the error, and its magnitude is proportional to the amount of error. Therefore, the phase of the ac signal is related to the polarity of the dc signal, and the magnitude of the ac signal is proportional to the dc signal voltage.

The modulator circuits use elements that act as synchronous switches. Examples of these elements are transistors, crystal or metallic rectifiers, diodes, triodes, and mechanical contactors. The elements have a high front-to-back resistance ratio, so that current will flow through the switch only in one direction. The switches are operated at the carrier frequency, which is usually 60 or 400 hertz. The resulting pulsating voltage is proportional to the dc error voltage. The phase of the pulsating voltage is determined by the polarity of the dc error signal.

### Semiconductor Diode Modulator

The crystal diode modulator (fig. 1-18) consists of a diode bridge and transformer network. When a reference voltage is applied to transformer T1, diodes CR2 and CR3 conduct during the negative alternation of the reference voltage. (There is a 180° phase reversal in T1.) Conversely, diodes CR1 and CR4 conduct on the positive half cycle of the reference voltage. Electron flow during the positive and negative alternations is represented by dotted arrows and solid arrows, respectively. If a positive dc signal voltage is applied during the negative-going alternation, electrons will flow from ground, through the upper half of the primary winding of transformer T2, through diode CR2, and through the upper half of the secondary winding of transformer T1 to the dc source. Current flow through the bottom of T2, CR4, and the bottom of T1 secondary is opposed by the opposite polarity across CR4. On the positive-going alternation, electrons will flow from ground, through the lower half of the primary of transformer T2, through diode CR4, and through transformer T1 to the dc signal source.

If a negative dc signal is applied, electron flow through the circuit will be reversed. That is, electrons will flow from the dc signal source, through diodes CR3 and CR1 in turn, to ground. Since, in all cases electrons are caused to flow through the primary of transformer T1 at the rate of the reference voltage, the output of this transformer will be at the frequency of the reference voltage. The phase of the ac output signal is determined at any given instant by both polarity of the dc input and the phase of the ac reference voltage.

### Electron Tube Modulators

An example of an electronic modulator is shown in figure 1-19. The input dc error voltage is impressed between E1 and ground. The ac reference voltage along with the action of V1, V2, R2, and R3 effectively clamp output E2 at zero potential for one-half cycle of the reference voltage. To accomplish this, the following conditions must exist:

- R1 must be much larger than R2.
- R2 and R3 are equal.
- V1 and V2 must be matched (usually a balance circuit is included to match the tubes).

With a reference voltage applied, making the plate of V2 positive and the cathode of V1 negative,

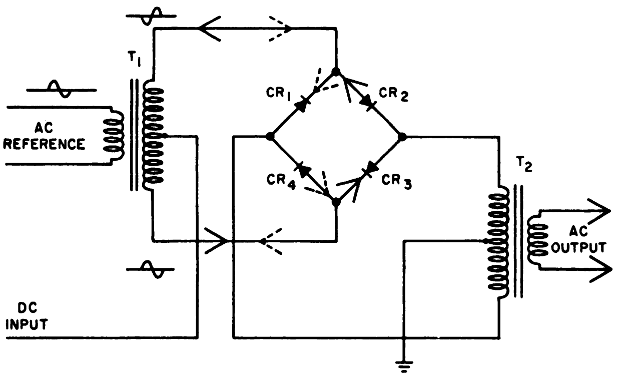

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Figure 1-18.—Semiconductor diode modulator.

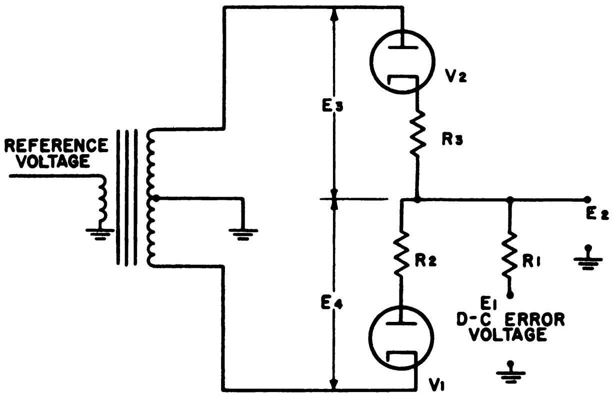

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Figure 1-19.—Electronic modulator.

current will flow through V1, R2, R3, and V2. Since R2 equals R3, voltage E3 will equal E4.

If the dc error voltage is positive, V1 will pass current down across R1, effectively dropping the amount of the error signal. The voltage output at E2 for this half cycle will be zero. If the dc error voltage is negative, current will pass up across R1, R3, and through V2 to the source. R1 once again (because of its size) drops an amount almost equal to the dc error voltage and the signal at E2 will again be almost zero.

We can readily see that when the tubes conduct, the voltage at E2 will be almost zero, and when they are cut off by the reverse polarity of the reference voltage, the output voltage will be equal to the dc error input. This will result in a pulsating dc output with its amplitude and phase determined by the amplitude and polarity of the dc error voltage.

## DEMODULATORS

Some fire control servos use dc servomotors to drive the load. An example is the amplidyne power drive. Amplidyne power drives are discussed later in this chapter. The input signal to an amplidyne servo is usually an ac synchro voltage. This requires that the ac order signal be converted to a dc signal. To accomplish this, a demodulator circuit is used. Demodulation is the process of extracting the signal intelligence from a modulated carrier wave. In the amplidyne type servo, the modulated carrier wave is the ac signal from the CTs. The magnitude of the ac signal is proportional to the size of the error and the phase of the intelligence we must extract.

To derive a dc signal having the same intelligence as the ac signal, we must be able to detect both the phase and the magnitude of the ac signal. The polarity of the dc signal is determined by the phase of the ac signal compared to a reference voltage. The reference voltage must be from the same source as the synchro supply, which is the voltage we modulated in the first place. The magnitude of the dc signal is directly proportional to that of the ac signal.

Demodulators are often referred to as phase-sensitive rectifiers or detectors, phase-discrimination converters, or simply as discriminators and detectors. These are high-sounding names for, as you will see, a circuit with which you are fairly familiar. If you understand the operating principles of modulators, it will be easy for you to learn the operating principles of the different types of demodulators.

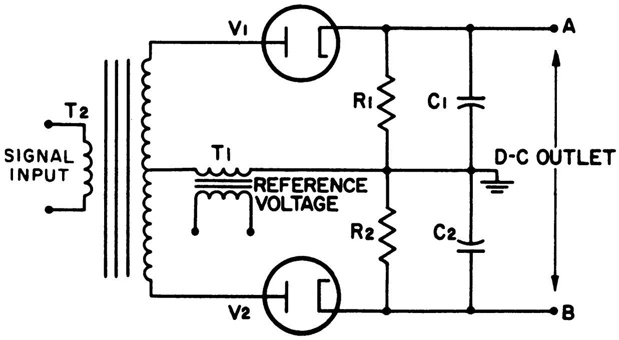

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Figure 1-20.—Electronic demodulator.

### Diode Demodulators

A typical diode demodulator (phase detector) is shown in figure 1-20. As illustrated, an ac supply voltage serves as the reference voltage for the detector. This voltage must come from the same source that is supply ac excitation to the synchro system, or whatever type of error detector is used, and must be in phase with the common supply voltage. This permits a phase-comparison of the error voltage with the reference voltage. The plates of the two diodes are supplied with this reference voltage in such a manner that the two plates will be in phase. Assuming there is no error signal from T2 to the plates of the diodes at the time the plates are on a positive half cycle, the two diodes will conduct equally. The voltages produced across R1 and R2 are equal, making the cathode of V1 and V2 at equal potential with respect to ground. With the two output terminals at the same potential, the output voltage will remain at zero as long as no error signal is applied.

If an error signal is applied to T2 making the plate of V1 positive at the same time the reference voltage on the plates of V1 and V2 is on its positive half cycle, V1 conduction will be increased and V2 conduction decreased over the no-signal condition. Since the voltages applied to the plates are both alternating, the voltage developed across R1 and R2 would also be alternating. However, R1-C1 and R2-C2 have a long time constant compared to the input frequency, and therefore filter most of the ripple, giving a dc output.

If the error signal applied to T2 is changed by 180 degrees, V2 would now increase its conduction while the conduction of V1 would be reduced. This would result in an output voltage of reversed polarity. Variations of the diode phase detector may be encountered; however, they all depend on the same basic principles of operation.

**Electric Demodulator**

The demodulator shown in figure 1-21 will rectify an ac signal and convert it to a pulsating dc signal proportional in magnitude to the input signal voltage. The polarity of the dc output voltage is determined by the phase of the signal compared to the reference voltage. Naturally, the signal and reference voltages are of the same frequency.

We will assume that the signal voltage on transformer T2 is in phase with the reference voltage on transformer T1. In the half cycle shown, the current depicted by the dotted arrows starts at terminal 6 of T1, flows through the rectifier CR2, winding 5-4 of T2, and parallel resistors R2 and R4 to terminal 7 of T1. The signal and reference voltages in these secondary windings of the transformers are in additive series. Therefore, the voltage across the parallel resistors is proportional to their sum.

The current depicted by the solid arrows starts at terminal 3 of T1, flows through rectifier CR3, winding 3-4 of T2, and parallel resistors R1 and R3, to terminal 4 of T1. The voltages in both these transformer windings are in subtractive series. Therefore, the voltage across the resistors is proportional to their difference.

Consequently, the voltage across resistors R1 and R3 is smaller than the voltage across the resistors R2 and R4. The resultant voltage across the resistor network and at the output terminals is the algebraic sum of the two voltages. The polarity of the output voltage is the same as that of the greater voltage.

On the next half cycle, the signal and reference voltages are still in phase. You should be able to trace the current flow in the demodulator mentally without the arrows. We will start at terminal 5 of T1, which is now negative, through CR1, winding 5-4 of T2, and parallel resistors R1 and R3, to terminal 4 of T1, which is now positive with respect to terminal 5. The voltages are still in subtractive series.

In the other pair of windings, we will start at terminal 8 of T1, which is now negative. From terminal 8, the current flows through CR4, winding 3-4 of T2, and the resistors R2 and R4, to terminal 7 of T1, which is now positive with respect to terminal 8. The voltages in the secondary windings of T1 and T2 are still in additive series.

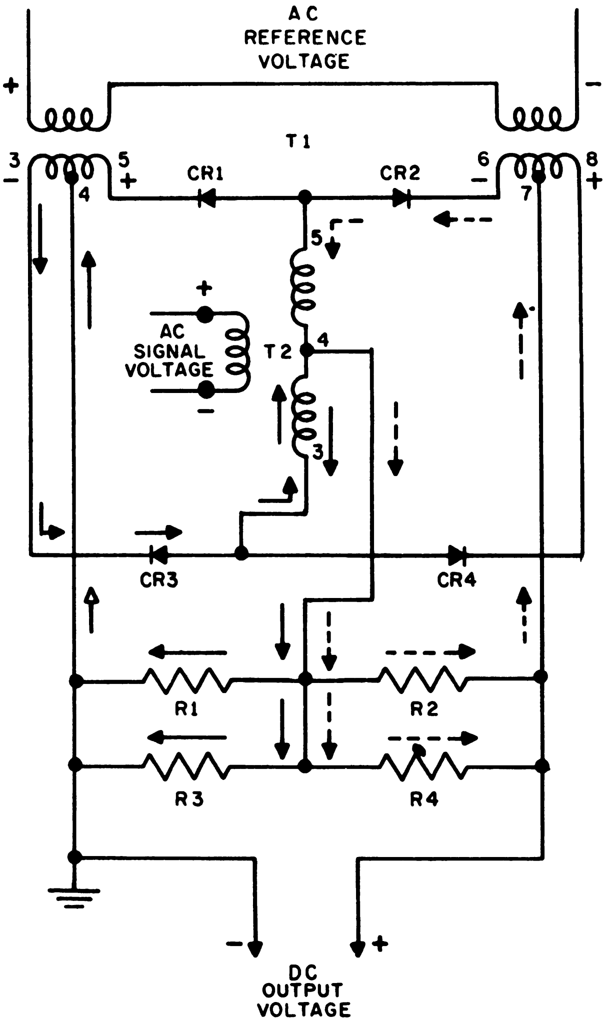

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Figure 1-21.—Electric demodulator.

Hence, the voltage across the resistor network is the same for both half cycles, and the output from the demodulator is a pulsating dc voltage.

If we assume the signal voltage is 180 degrees out of phase with the reference voltage, the direction of the current flow through the resistor network would be reversed. The voltage across R1 and R3 would now be larger than the voltage across R2 and R4. Therefore, the polarity of the output voltage would be reversed.

The peak-to-peak value of the reference voltage is constant; therefore, the magnitude of the output is determined by the size of the error signal. With no signal present, the reference voltage drop across the resistor networks would be equal and opposite, and there would be no output. This balance is disturbed by the error signal.

## SERVO AMPLIFIERS

Servo amplifiers have several inherent advantages:

- Flat amplitude response or gain over the broad band of frequencies of interest

- Small and fixed phase-shift of the output with respect to the input

- Low output impedance and low nonlinearity of amplifiers

- Low noise level

It is not practical to discuss individual amplifiers in this text. But we have selected representative amplifiers to indicate the various functions they perform in a servo. This discussion will help you to classify and to understand the amplifiers in your equipment.

### Preamplifiers

In some equipment standard servo amplifiers are used. This is particularly true in instruments that have module plug-in amplifiers. Therefore, the input signal must be fairly standard within the limits of the amplifier. But servo error generators vary. For example, the error signal's amplitude may be too small for a standard amplifier, and a preamplifier is used. The preamplifier is a separate stage used to bring the signal characteristics within the requirements of the amplifier.

### Transistor Power Amplifier

Figure 1-22 shows a two-stage transistor amplifier of the plug-in module type. We will

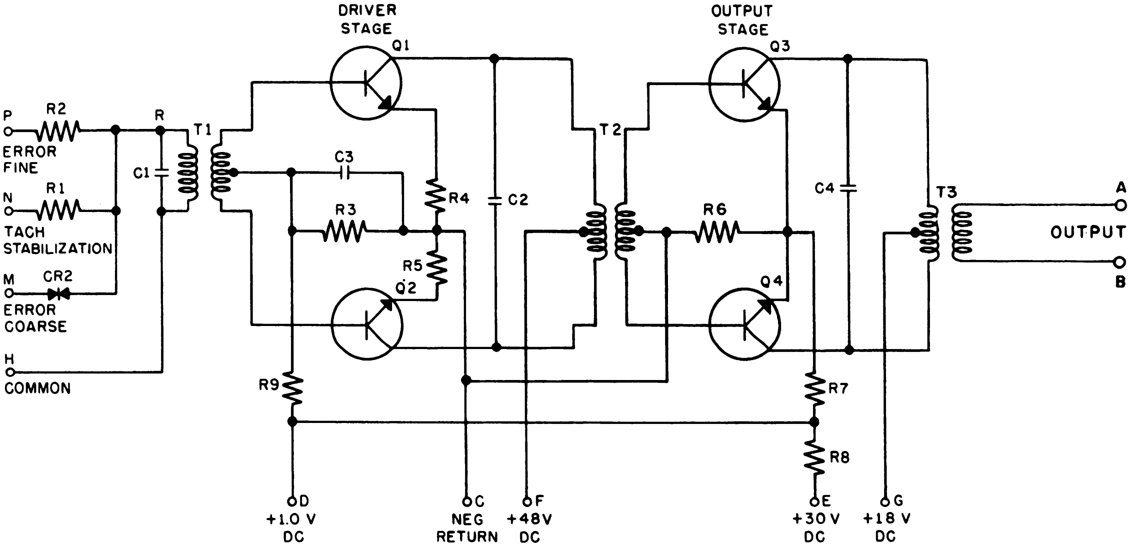

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Figure 1-22.—Transistor power amplifier.

assume the input error signals on pins P and M are from a dual-speed synchro control system. Zener diode CR2 is part of the synchronizing circuit and works as two diodes connected back to back. The fine signal on pin P is normally in control. If the coarse signal becomes sufficiently large, it will break down the diodes and assume control. The input on pin N is a feedback voltage from a tachometer generator. We will discuss stabilization of the servo separately later in the chapter.

The sum of the voltages on pins P, M, and N is applied to the input transformer T1. The other terminal of T1 is connected to pin H, which is a common return for the CTs and the tach. There are four supply voltages—the + 1 V dc and the + 30 V dc are used in a bias network, the + 48 V dc is used as collector supply for the first stage, and the + 18 V dc is used as the collector supply for the output stage.

Resistors R3, R6, R7, R8, and R9 form a voltage divided network to provide a fixed base-emitter bias on the transistors. The circuit for the + 1 V bias is from pin D through R9 and R3 back to the negative side, pin C. The bases of Q1 and Q2 are connected to the bias circuit at the tie point between R9 and R3 through the winding of the input transformer T1. Because of the need for good voltage regulation, it is desirable not to have current flow in this circuit. Therefore, the + 1 V bias circuit is connected to the + 30 V bias circuit at the junction of resistors R7 and R8. There is approximately + 1.0 volts at this junction, and most of the current drawn by the base-emitter circuit comes from the + 30 V dc source. Consequently, the + 1 V bias supply is not loaded down, and voltage regulation is good.

The circuit for the + 30 bias voltage is from pin E through R8, R7, and R6 back to the negative side, pin C. The base Q3 and Q4 are connected to the bias circuit through the winding of T2, the interstage transformer. The + 30 bias voltage is connected to the + 1 V bias voltage at the junction of R8 and R7. Thus, in the biasing circuits, R9 and R3 are in parallel with R7 and R6.

The collectors of the first stage transistors, Q1 and Q2, are connected to the + 48 volt supply at pin F through the primary winding of T2. The error signals from the opposite ends of T1 to the bases of Q1 and Q2 are 180 degrees out of phase with one another. The output from this stage is from the collectors, which are connected to the primary of T2 in opposition. The stage is arranged in push-pull as a driver for the second stage. The transistors are arranged in a base input/collector output circuit, with grounded emitters. The emitters are connected through R4 and R5 to the negative side. The resistors R4 and R5 furnish self-bias and help to stabilize the transistor circuits.

Transformer T2 couples the amplified error signal to the second stage. Transistors Q3 and Q4 are base input/collector output and are connected as a push-pull grounded-emitter circuit in an arrangement similar to the first stage. The required signal inversion is obtained from the transformer. The output of the amplifier, at pins A and B, is connected to a split-phase servomotor. The motor drives the load and the feedback tachometer generator. Response from the motor repositions the CTs to null out the error signal.

The dc voltages to the transistor's collectors are unfiltered and contain a ripple that is in phase with the reference voltage of the synchro system. Therefore, the error signal is either in phase or 180 degrees out of phase with the ac component in the collector voltages. This eliminates the need for a separate demodulator and modulator circuit.

### Electron Tube Servo Amplifier

Figure 1-23 shows a representative electron tube servo amplifier. We can divide the amplifier into the following functional sections: Tubes V1 and V2 are voltage amplifiers, tube V3 is a phase-inverter and driver stage, and tubes V4 and V5 are the output stage connected in push-pull. The inputs to the amplifier are as follows: The error signal on terminal 3, the plate supply voltages of + 450 and + 300 on terminals 4 and 5, a biasing voltage of + 105 on

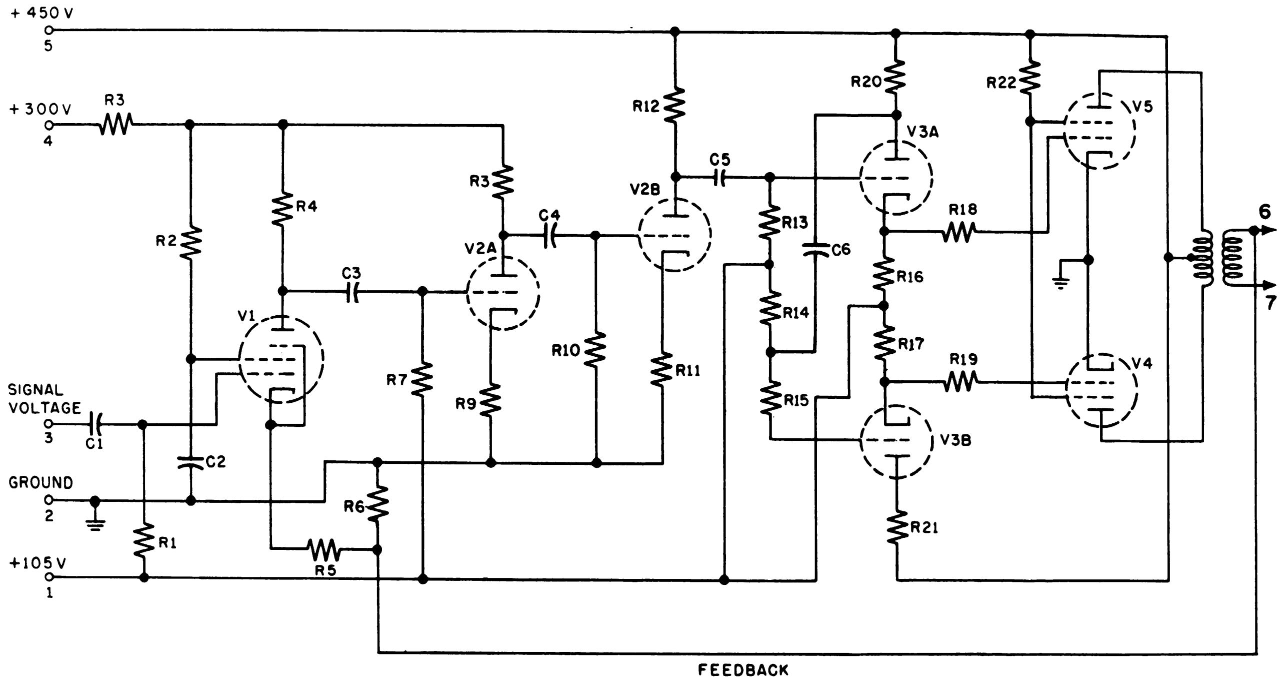

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Figure 1-23.—Electron tube servo amplifier.

terminal 1, and an instrument ground on terminal 2. The output is taken from terminals 6 and 7.

We will assume the servo amplifier is used with a dual-speed synchro control system. The input signal on terminal 3 is from a relay-operated synchronizing circuit. The signal to tube V1, a high-gain pentode voltage amplifier, is developed across the resistor R1. The output from V1 is taken from the plate and coupled to V2A through C3. The second and third stages are medium-gain voltage amplifiers consisting of the twin triode V2. The two sections of V2 are coupled by RC circuits. The output from V2B is coupled to the grid of V3A.

Both sections of V3 are connected as cathode followers to drive the output stage. The two signals are coupled directly to V4 and V5 through R18 and R19. However, V3A has two outputs; the signal from its plate to V3B through C6 and R15 is phase inverted from its cathode output. If we assume there is no error signal on the grid of V3A, the bias on both sections of the tube results in the cathodes being at the same potential. Therefore, the signals to the grids of V4 and V5 are equal. Now assume that a positive signal is applied to the grid of V3A. The positive signal causes the conduction through V3A to increase proportionally to the size of the signal. The increased current flow causes the cathode to swing in the positive direction and the plate potential to drop. Thus, the swing of the plate is a negative signal to the grid of V3B, which reduces the current flow through V3B. The cathode potential drops in proportion to the signal on its grid. Thus, the cathode of V3A has changed in a positive direction while the cathode of V3B has changed an equal amount in the negative direction. Naturally, if the signal to the grid of V3A is negative, all the resulting signals would be in the opposite direction.

Tubes V4 and V5 are connected in push-pull across the output transformer T1. The bias on the tubes is controlled by V3—the driver stage. If there is no error signal present on the grid of V3A, the output tubes conduct an equal amount in opposite directions through the primary winding of T1. The output of the amplifier is zero.

Since the signals to the grids are in opposite directions, conduction increases in one tube but decreases in the other. The amplifier then has an output. The phase of the output is determined by the polarity of the signals to the grids, and its magnitude is proportional to the magnitude of the grid signals.

A sample of the output voltage is applied to the cathode of V1 as negative feedback. The feedback voltage contains the noise components generated in the amplifier, but their phase is inverted. Hence, the feedback voltage tends to eliminate this source of noise voltage, and also helps to stabilize the amplifier. Note that there are two sources of plate supply in the amplifier. The source for the last three stages of the amplifier is independent of the supply for the two high-gain voltage stages. This reduces the amount of undesirable fluctuations in the plate supply that is coupled between the two sections of the amplifier. The filter circuit, R2 and C2, forms a shunt across V1. This circuit decouples or shunts undesirable frequencies from the amplifier.

### Magnetic Amplifiers

In electron tube amplifiers, the amount of current that flows through a tube is controlled by its internal impedance. A reduction of the impedance increases the current flow through the tube. Magnetic amplifiers use the same principle. The impedance, and consequently the current in a saturable reaction, can be controlled by varying the magnetic state of its core.

**BASIC SATURABLE REACTION.**—Basically, the saturable reactor circuit has a control winding and a load winding on each of two toroidal cores (fig. 1-24). The control windings are connected so their magnetic fields have opposite polarities. The signal resistor has a low ohmic value and the control windings have a small number of turns. The load windings present an infinite impedance when there is no signal input to the control windings, and the load current is practically zero.

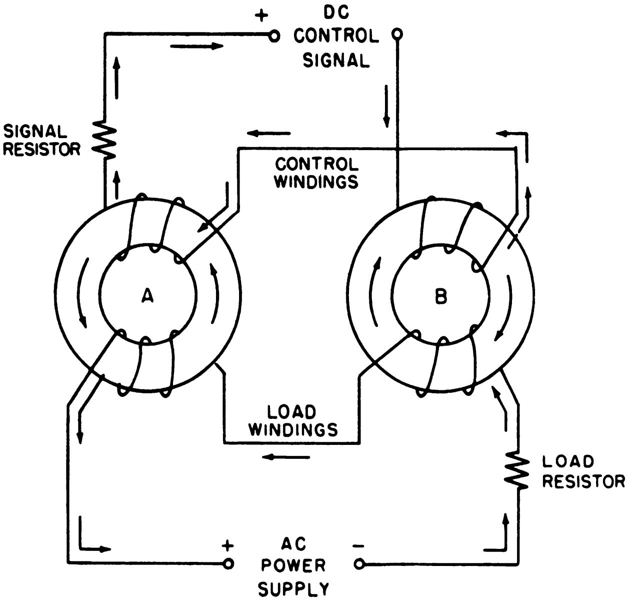

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Figure 1-24.—Basic saturable reactor.

A dc control signal impressed on the control windings creates magnetic fields in cores A and B. The magnetic fields are stationary and opposite in polarity. The fluctuating magnetic fields created by the ac power supply have the same polarity in both cores and are additive in one core and subtractive in the other core with the control magnetic fields. When the ac power, during its first half cycle, creates additive fields in core B and subtractive fields in core A, there is a point where core B becomes saturated. The load winding on core B immediately drops towards zero impedance, because, with constant flux density, there is no change in turns linkage as the ac voltage varies. At the same time, the impedance of the load winding of core A is considerably reduced. The subtractive magnetic fields reduce the total flux density until there is only a small rate of change of turns linkages as the ac voltage varies. With low total flux density, the windings on core A begin to function as a transformer. At this point, the control windings appear as a short circuit, and the impedance of the load windings is reduced further toward zero. Therefore, almost the entire voltage of the ac power supply is impressed on the load resistor.

During the second half cycle of the ac supply, core A becomes saturated and core B functions as a transformer. The load resistor receives almost the entire voltage of the ac supply, but of the opposite phase. The amount of current through the load resistor is determined by the point in the ac cycle when one of the cores becomes saturated. The saturation point is determined by the dc control signal's amplitude. When the dc signal is greater, saturation is reached earlier, and the period that load current flows in each cycle lengthens. Thus, more current is used at the load.

The basic saturable reactor circuit does not have the stability or accuracy required for use in magnetic amplifiers in fire control equipment. To obtain better operation, the reactors have several additional windings. A regenerative winding is used with the load winding, and a bias and a negative feedback winding are used with the control windings.

**REGENERATIVE WINDINGS.**—The load windings are connected in series to a full-wave rectifier bridge (fig. 1-25). The regenerative windings are connected in series bucking across the bridge. When a dc control signal is present, during the first half cycle of the ac supply voltage, the current through the regenerative windings creates a magnetic field of the same polarity as created by the load and control current in one core. This core (A in the figure) will drive quickly to saturation and cause the inpedance of the load winding to drop to near zero. At the same time, the magnetic fields created in the other core (B in the figure) by the load and regenerative windings tend to cancel each other, leaving only the low-density flux created by the dc control signal. This core acts as a transformer, in which the near zero impedance of the control winding is reflected in the load winding.

In the second half cycle of the ac, the current direction remains the same, except through the load windings and the load. Core B becomes saturated, and load winding B has near zero impedance. Load winding A now acts as the transformer.

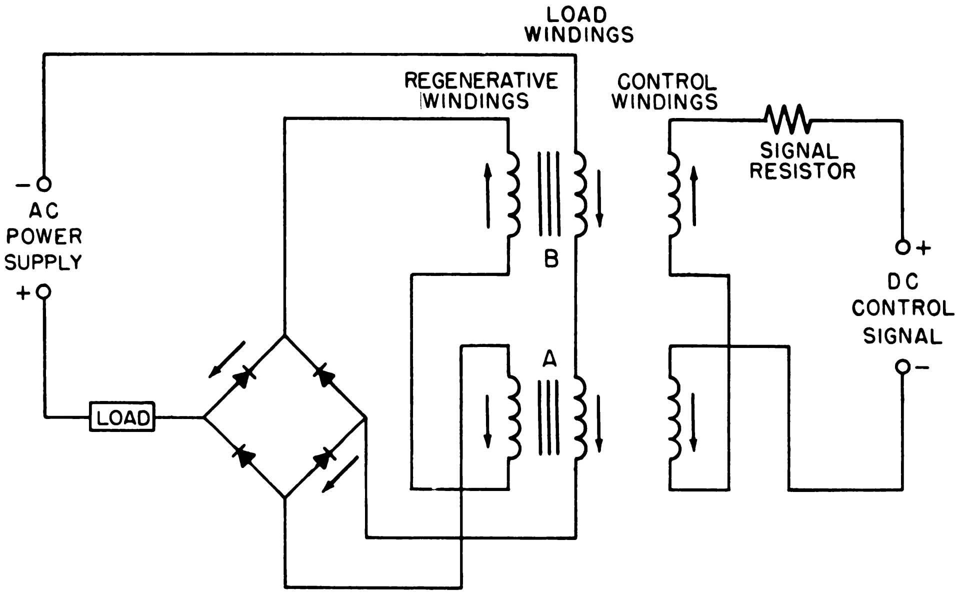

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Figure 1-25.—Regenerative windings.

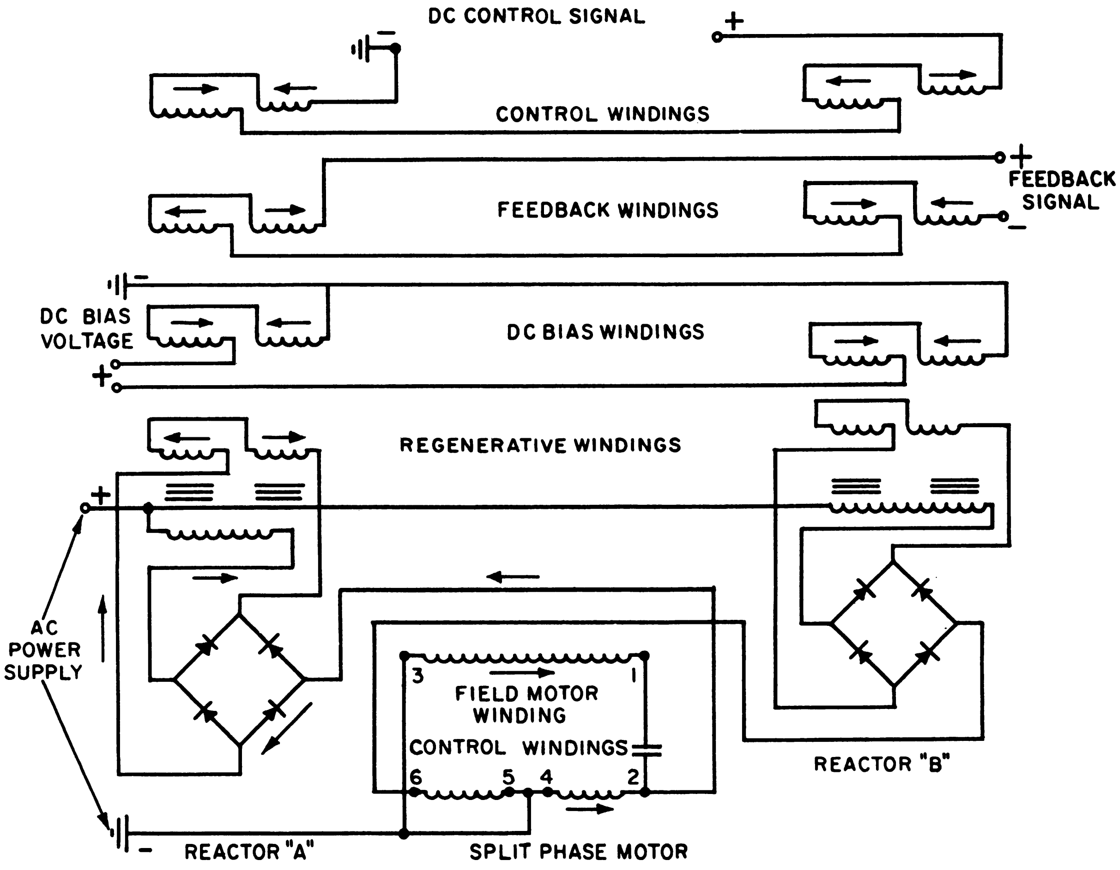

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Figure 1-26.—Magnetic amplifier in a servo.

**MAGNETIC AMPLIFIER IN A SERVO.**— Figure 1-26 shows a practical bidirectional servo with a magnetic amplifier consisting of two saturable reactors. One half of the control winding of the ac servomotor acts as the load on each reactor. The direction of the motor rotation is determined by selecting the half of the control winding through which current will flow. The saturable reactors A and B are similar to the one in figure 1-25 with the exception that we have added the bias and negative feedback windings.

**BIAS AND FEEDBACK WINDINGS.**— The efficiency and accuracy of a magnetic amplifier are lowered by the magnetic hysteresis of the core material. *Hysteresis* is the lag of the magnetic flux behind the current that causes it. The two bias windings in each reactor are wound in opposite directions. Therefore, the magnetic fields created by the dc bias current have opposite polarities. To counteract the lag, the bias magnetic fields tend to cause the magnetic fields in the core to reverse polarities with the ac voltage supply. The amplitude and direction of the bias current is set so that when the control signal has the same polarity it will prevent reaction B in the figure from saturating. When the bias and control signals have opposite polarities, the bias will stop reactor A from conducting.

The dc control signal (figure 1-26) is positive, and saturable reactor A will conduct. The direction of current flow through the motor's control winding 2-4, which is the load on the reactor, corresponds to the current in the motor's field winding 1-3. During the negative half cycle of the ac supply, the current in both the control and field windings of the motor will reverse. Therefore, the motor will continue to drive in the same direction. Basically, the operation of the saturable reactor is identical to the one in figure 1-25. As long as the input control signal polarity remains the same, reactor A will continue to conduct. Reactor B is prevented from conducting by its bias voltage.

If the polarity of the input signal becomes negative, reactor B will conduct and pass current through motor control winding 5-6. Current direction through the motor control winding is opposite to that in the motor field windings. The motor will now rotate in the opposite direction. Reactor A is prevented from saturating by its bias current. Thus, we have a bidirectional servo system.

The negative feedback voltage is taken from the output motion of the servo. Its polarity is opposite to that of the control signal voltage input to the amplifier. The feedback voltage serves the same purpose as in an electron tube amplifier. It will dampen the servo, reduce the noise in the output generated in the amplifier, and help to stabilize the system.

### Isolation Amplifiers

Isolation amplifiers are used with computing components, such as resolvers and potentiometers, to increase their accuracy. Some other names for an isolation amplifier are buffer, booster, and operational amplifier. The amplifier has a high input impedance and thus draws practically no current from the signal source. It separates the signal source from its normal load, and inaccuracies that would result from loading the signal source are thereby greatly reduced. A resolver's output signal is a scale voltage representing a quantity in the fire control problem. We cannot afford errors in the scale voltage.

The isolation amplifier is a power amplifier with a voltage gain slightly greater than unity. Its output voltage has either no phase shift or a designed and controlled phase shift. The voltage gain beyond unity compensates for the losses incurred in the particular component with which it is used.

**BASIC ISOLATION AMPLIFIER CIRCUIT.**—The isolation amplifier eliminates direct connections between the signal generator and the resolver Re1 and its load resolver Re2 (fig. 1-27). The amplifier is in series with the load. First, we will consider the voltage regulating circuit and trace out the heavy lined loop. The input to the amplifier is the instantaneous potential difference between R1 of Re1 and

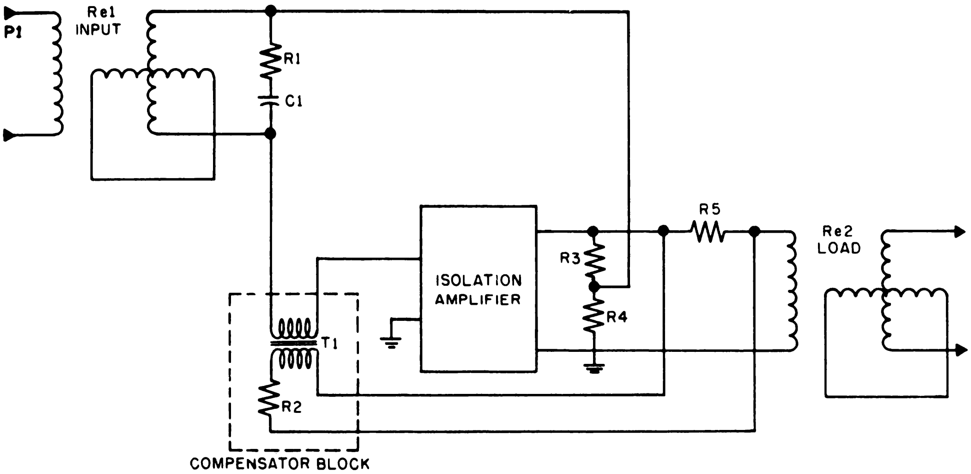

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Figure 1-27.—Isolation amplifier circuit.

ground. The amplifier's outputs are taken from the voltage dividers R3 and R4. The voltage across the resistors is applied to Re2, the load. Resistor R4 determines the amount of negative feedback to Re1 and the amplifier. The value of R4 is selected so that the feedback is slightly greater than unity to make up for resolver transformation losses.

The portion of the amplifier's output across R4 is connected back to the signal source, Re1. We can look at the negative feedback voltage as a balancing voltage supply. When Re1 produces a signal to the amplifier, the feedback voltage, whose amplitude is proportional to the signal voltage, is sent back to balance it. Thus, the signal from Re1 "sees" the impedance of the

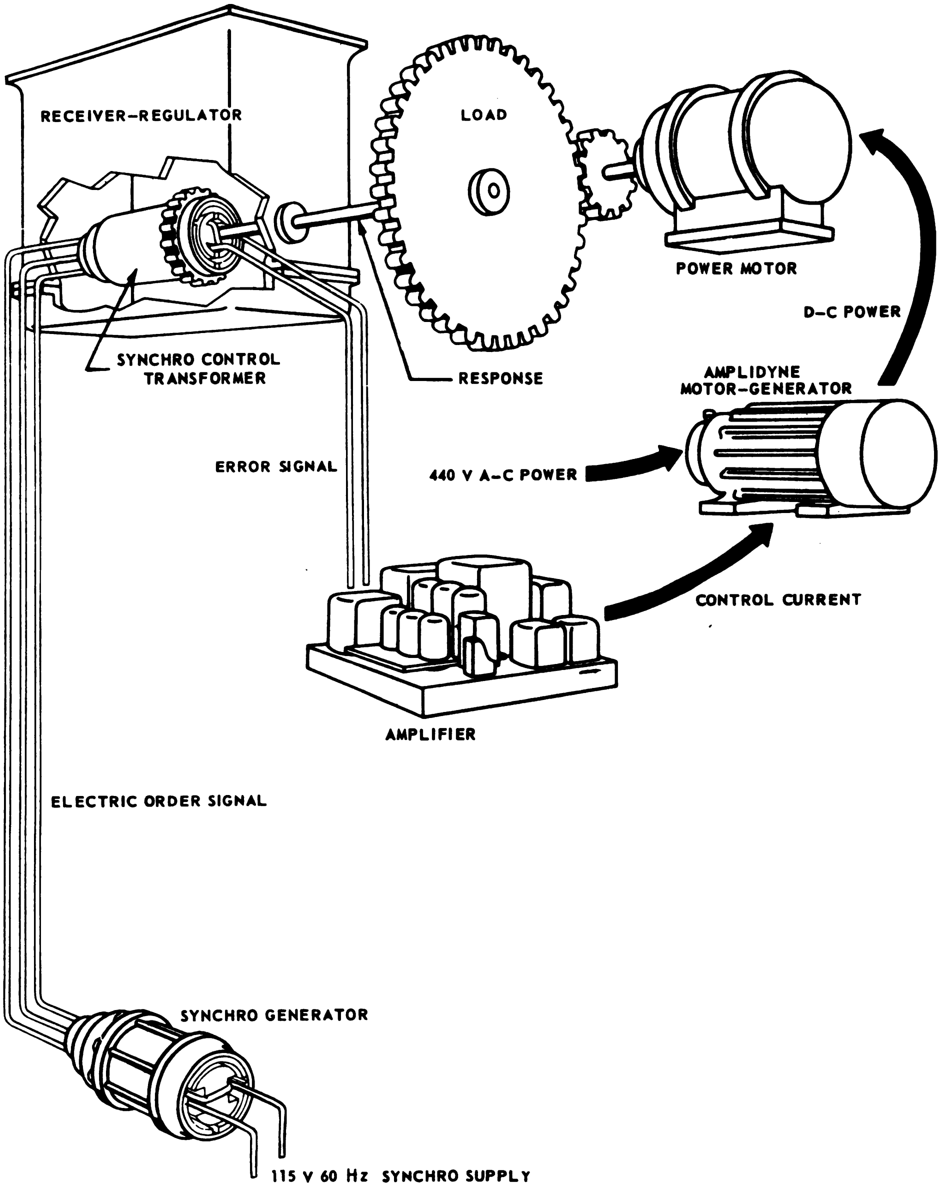

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Figure 1-28.—Basic amplidyne drive.

amplifier input circuit plus the impedance of a related but separate source of supply in the feedback circuit. Therefore, practically no current is drawn from Re1, and the signal voltage is constant and regulated. The load current for Re2 is drawn from the amplifier and not from the signal generator Re1.

**PHASE COMPENSATOR CIRCUIT.**—We can control the phase shift in the amplifier by circuit design. But what of the phase shift caused by the inductive load in Re2? The inductive reactance of the coil causes the load current to lag its voltage by almost 90 degrees (fig. 1-27). The resistance of R5 is small compared to the inductive reactance of the coil. The voltage across R5 is developed by the load current, and, therefore, it is in phase with the current and lags the load voltage by almost 90 degrees. The R5 voltage is a measure of the phase shift caused by the load reactance and is used as a feedback voltage.

The feedback voltage is combined with the input to the amplifier at T1. This feedback, since it lags approximately 90 degrees, is often referred to as quadrature feedback; it shifts the phase of the input signal just enough to cancel the phase shift in the Re2 coil. Thus, the compensator network maintains the Re2 input at the same phase as the Re1 output.

### Amplidynes

An *amplidyne drive* is a servo system that uses both a conventional electronic amplifier and a rotary amplifier (amplidyne generator) to supply controlled power to position heavy loads. Figure 1-28 shows a typical amplidyne drive.

**AMPLIFIER.**—The amplifier in the diagram rectifies and amplifies the ac error signal. The output stage of the amplifier is arranged in push-pull configuration. Thus, the output of the amplifier is two opposing dc currents. This output furnishes the control currents for the amplidyne generator. The amplidyne generator is the rotary amplifier of the power drive. This is the instrument that amplifies a low-powered signal into one strong enough to drive the director. If the principles of dc generators (particularly armature reaction) and amplidyne generators are hazy in your mind, review the NEETS modules on ac and dc motors and generators.

**AMPLIDYNE GENERATOR.**—Figure 1-29 is a simplified schematic diagram of the amplidyne generator, the drive motors, and their associated circuits. A conventional ac induction motor drives the generator. The generator is rotated in one direction at a constant speed. The generator excitation is supplied by the control windings F1-F2 and F3-F4. The control windings

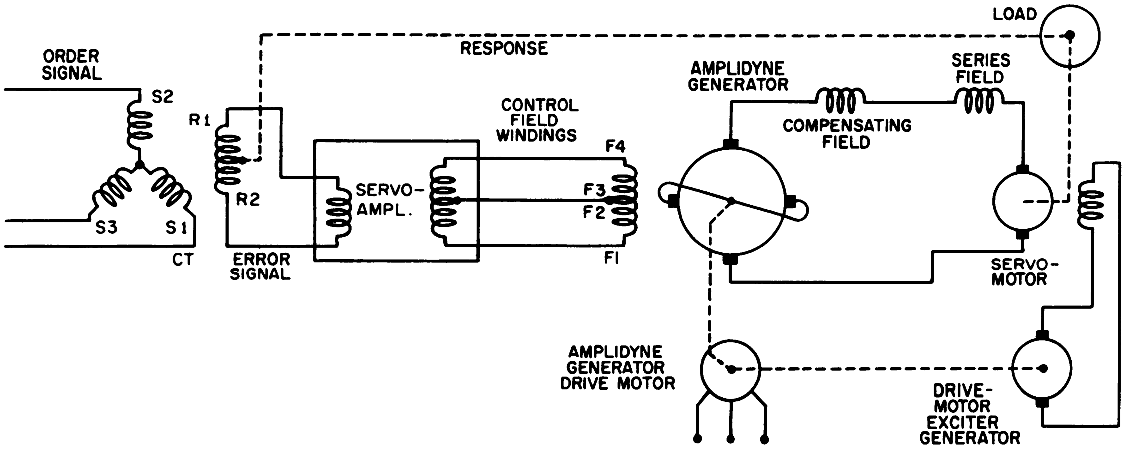

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Figure 1-29.—Simplified diagram of the amplidyne generator and associated circuits.

are energized by the opposing dc currents from the amplifier. These windings create a magnetic field that is the resultant of both currents. With a zero error signal to the amplifier, the dc outputs are equal and opposite; therefore, they cancel, and no control field is present in the generator. When there is an error signal to the amplifier, one of the dc currents will increase while the other will decrease a like amount, and a resultant magnetic control field will be present in the generator.

The control field causes a relatively large current in the armature winding that is shorted by the brushes. This armature current creates a strong quadrature field. The unshorted armature windings cut the quadrature field causing a large current in the windings. This current is delivered to the load by the load brushes.

The magnitude of the generator output is determined by the strength of the control field. The polarity of the generator output is determined by the polarity of the control field. Thus, both the magnitude and polarity of the generator output are determined by the dc current input from the amplifier. Later in the chapter, we will see how the amplifier determines, from the ac error signal, which dc output should be the stronger.

The compensating winding in the generator is used to compensate for armature reaction. Armature reaction is caused by the magnetic field created by the current delivered to the load. This current passes through the compensating winding, which creates a magnetic field. The compensating winding magnetic field and the load current magnetic field cancel each other.

This is fundamentally how an amplidyne generator works, although other refinements are necessary to achieve the fast stable operation that is needed in driving a fire control director.

**DRIVE MOTOR.**—The drive motor is a dc motor of conventional design, having an armature circuit and a magnetic field. In a permanent-magnet dc motor, the magnetic field is supplied by permanent magnets built into the stator. In the separately excited type, the magnetic field is provided by a stator winding that receives a steady dc current from a source separate from the motor. In both types, the armature current comes directly from the amplidyne generator.

The drive motor has a steady excitation field. Thus, the direction of rotation depends only on the direction of the current in the armature. The torque applied by the motor to the load depends on the volume of this current. Therefore, the motor's direction of rotation and torque depend on the output of the amplidyne generator.

**FEEDBACK CIRCUITS.**—To keep the director's los on target, the power drives must be very sensitive to changing input signals. But, stable operation is definitely a requirement of the power drives. Feedback voltages are used to stabilize the operation of the power drives. The number of feedback voltages and their strength are determined by load characteristics and by the type of response required. These stabilizing voltages modify the effect of the power drive input error signal, but do not interfere with normal operation.

There are three stabilizing voltages commonly used in amplidyne follow-up systems—speed, current, and jitter voltages. Figure 1-30 shows the source of these voltages in the train follow-up system.

**Source of the Stabilizing Voltages.**—The speed voltage is obtained from a dc tachometer generator, which is geared to the train drive. This makes the generator output proportional to the director's speed. The output polarity depends upon the direction of movement of the director. In the diagram, you can see that this voltage is dropped across potentiometer R18. This voltage opposes the error signal and thus governs, to some extent, the errors on speeding up and slowing down the director.

The current stabilizing voltage is obtained from the series field of the drive motor. The voltage across the series field is proportional to the current drawn by the drive motor. This voltage is most effective when the drive motor draws heavy current; for example, at starts and reversals. This voltage is dropped across potentiometer R17.

To obtain the third stabilizing voltage, a special winding is built into the stator of the amplidyne generator (fig. 1-30). This winding is called the *quadrature winding*, and it is placed at a right angle to the control winding. In this position, the quadrature winding is cut by the

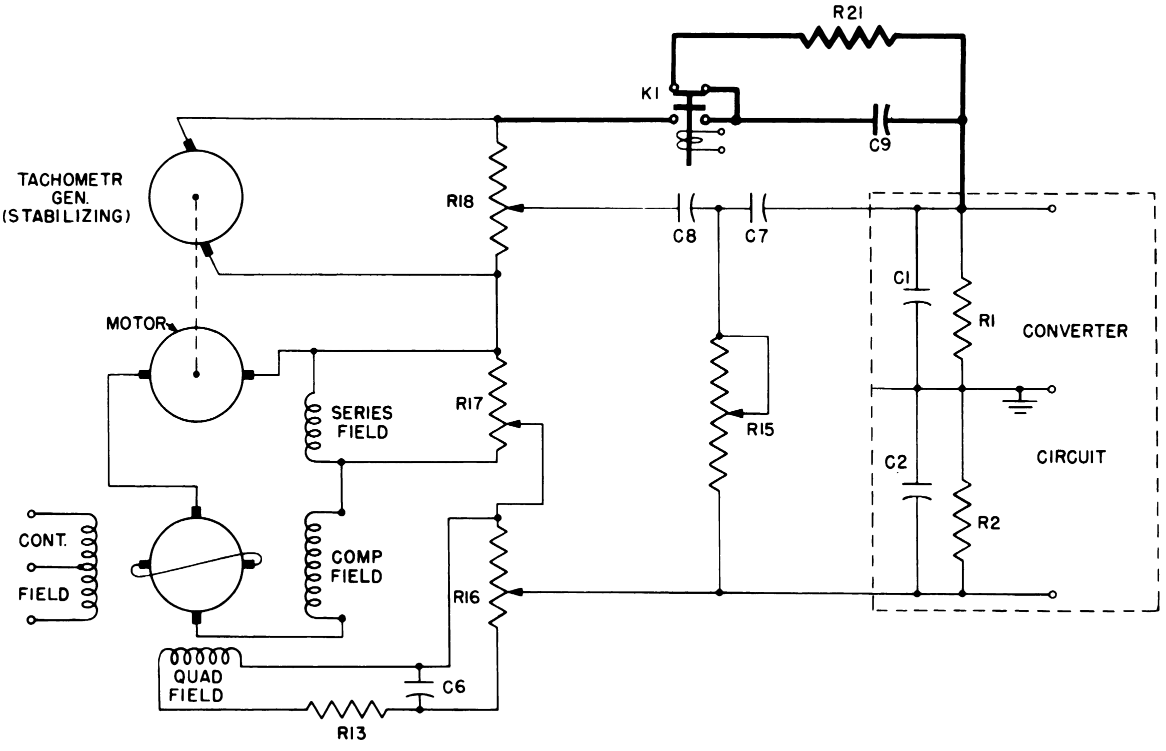

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Figure 1-30.—Stabilized circuit.

quadrature field. Since this field is created by a dc current, it has a constant magnitude when a constant signal is applied to the generator. The flux lines of the quadrature field thread through the winding and do not induce a voltage. But when the strength of the quadrature field changes, a voltage is induced in the winding. This happens only when the load on the amplidyne changes. Thus, the voltage induced in the quadrature winding is proportional to the rate of load change and the frequency of the quadrature flux changes.

The rate of load change is greatest when the director is reversing fastest, during jitter. For this reason, the voltage in the quadrature winding is called the *jitter stabilizing voltage*. The jitter voltage is dropped across potentiometer R16.

Every follow-up system has one or more natural oscillating frequencies that depend on the weight of the load, designed speed of the system, and other characteristics. In the train amplidyne system, all three of the stabilizing voltages are needed to control hunting and jitter. In other systems, the characteristics are such that only one or two of the signals are necessary.

**Combining the Stabilizing Voltage.**—As explained, each stabilizing voltage is used to overcome a particular type of oscillation. Since each of these voltages is applied to an adjustable potentiometer, the percentage of each voltage in the remainder of the circuit can be controlled. Therefore, we can adjust the amount of each of these voltages to obtain the best operation of the director. The potentiometers are connected in series. Thus, their output voltage will be the algebraic sum of the three voltage percentages.

The stabilizing voltages are direct current. As long as the director is operating normally and is moving at a constant speed, condensers C7 and C8 will effectively block the dc voltages (fig. 1-30). But when the director is oscillating, the polarity of the voltages is reversed on every swing, and they become low frequency ac voltages. The resulting alternating current can pass through the condensers. The condensers and their associated resistors will pass the frequencies found in oscillations, but will block the lower frequencies in the range of the roll and pitch of the ship. Hence, they constitute a high-pass filter. This results in no appreciable current flow in resistors R1 and R2, except when the system is unstable.

The potentials developed across R1 and R2 are determined by the direction of director movement. The two potentials of opposite polarity are used to modify the error signal in the converter stage of the amplifier. The potentials are always in opposition to the error signal and are thus a form of negative feedback.

Potentiometer R15 (figure 1-30) is in parallel with resistors R1 and R2. R15 provides a path for bypassing a part of the stabilizing current to adjust its total effect on the amplifier.

## COMPARISON OF AC AND DC SERVOS

Generally speaking, ac and dc servos are similar. They both meet the basic requirements of a fire control servo and have essentially the same components. The type of servo used is determined by the requirements of the load. Heavy loads with a wide speed range, such as directors and radar antennas, are controlled primarily by dc servos. Light loads with a fairly constant speed requirement are normally controlled by ac servos. The characteristics of ac and dc servomechanisms will tell us why this is so.

### AC Servomotors

Large ac motors are too inefficient for servo use. To obtain the desired torque-speed output curve, the motor becomes too large, draws excessive power, and is difficult to cool. Hence, ac servos in fire control equipment are used primarily to control light loads that require low power. Most of the ac servomotors are of the two-phase or split-phase induction type. Fundamentally, these motors are constant-speed devices, although their speed can be varied within limits by varying the amplitude of the voltage to one of the motor's stator windings.

The voltages to the stator windings of a two-phase motor should be exactly 90 electrical degrees apart. The 90-degree phase relationship can be established by shifting the phase of the voltage to either of the stator windings. Any phase shift that changes the 90-degree relationship reduces the motor's efficiency. The direction of rotation of the motor can be changed by reversing the phase relationship between the stator windings.

### DC Servomotors

The control characteristics of dc servomotors are superior to those of ac servomotors. The dc servomotor can control heavy loads at variable speeds. Most of the dc servomotors found in fire control equipment are either the permanent magnet type (those used for light loads) or the shunt field type (those used for heavy loads). The operational characteristics of these motors are covered in NEETS, module 5. When they are used in servos, the strength of the motor's field (which is supplied by the magnet or shunt field) is held constant. The direction and the speed of the motor's rotation is determined by the armature current, which is supplied by the servo amplifier. An increase in armature current increases the motor's speed. A reversal of the motor's armature current will change the motor's direction of rotation.

A disadvantage of dc servo amplifiers is their tendency to drift. Drift is the low frequency variation of the output voltage with no change of the input. Drift is usually caused by changes in power supply voltages or by the change of component values because of temperature variations, aging effects, and humidity. Drift in dc servo amplifiers can be overcome by circuit design. Frequently, however, an ac amplifier is used and the output is demodulated. As a result, in some servos you may find modulation and demodulation stages that, on the surface at least, seem purposeless.

## OPERATIONAL ACCURACY

A servo should drive rapidly toward the fixed correspondence point of a steady state of static signal. It should synchronize with a minimum of motion in the shortest time. Once synchronized, the servo should hold its position rigidly at the correspondence point. Where the input order signal is continuously changing position, the servo must drive to the correspondence point in the same manner as with a fixed signal. Once in correspondence, the servo must drive at the same rate as the input order signal.

In a position control servo, the rate of movement is established by the rate of displacement. Hence, there is a definite lag between the order signal position and the output position.

The accuracy of a servo is determined by its ability to measure and produce an error signal and to amplify the error signal to a level that will move the load to eliminate the error. The overall accuracy of a servo is determined by the accuracy of its components and their input data.

The error detector receives and compares the ordered position and the actual position of the servo's output. Any error in the input data will naturally reduce the accuracy of the error detector's output. The accuracy of the error detector is determined by the amount of difference between its inputs that is necessary to produce a usable error signal.

The gain of the servo amplifier determines how large the error signal must be before amplifier output is sufficient to drive the error reducer. The higher the gain, the more sensitive the amplifier and the more accurate the servo. The efficiency of the error reducer determines how large the control current must be before it will drive.

The accuracy of the data, error detector, servo amplifier, and error reducer determines the static error or dead space of the servo. The static error is the angular displacement between the input and output of the servo under static conditions (synchronized to a fixed order signal). The static error under load is the angular lag between the input and output of the servo when the input signal is moving at a constant velocity. The static errors are sometimes called steady state errors.

We have taken a negative approach to accuracy to show that servos have inherent sources of errors. Because of the errors, the term *null voltage* is used rather than zero voltage when the servo is synchronized. But do not get the false impression of large errors; the accumulative error in fire control servos is small. Multiple-speed data transmission systems are used to increase the accuracy of servos, and servos have high gain amplifiers to increase accuracy.

## GAIN, PHASE, AND BALANCE ADJUSTMENTS

In many servo systems, the gain of the amplifier can be varied by an adjustment. The *gain adjustment* governs the amplitude or amount of the signal voltage applied to the amplifier or one of its stages. Normally, the highest gain possible, with the servo system possessing a satisfactory degree of stability, is the most desirable.

In ac servo systems, another adjustment that can control the sensitivity of the system is the phase adjustment. The *phase adjustment* is used to shift the phase relationship between the signal voltage and a reference voltage. In an amplifier with phase shift control, the grid signal is shifted in phase with reference to the plate voltage of a tube. The tube's firing point is delayed or advanced depending upon the phase shift of the grid signal. The phase shift can vary the firing time of the tube over the plate's entire positive alternation.

A phase control is included in some servo systems using ac motors. The two windings of the ac servomotor should be energized by ac voltages that are 90 degrees apart. This phase adjustment is included in the system to compensate for any phase shift in the amplifier circuit. The adjustment may be located in the control amplifier, or, in the case of a split-phase motor, it may be in the uncontrolled winding.

Servo systems using push-pull amplifiers must be balanced so that when there is no signal input to the amplifier, its output will be zero, and the servomotor will stand still with no creep. The push-pull amplifier must ensure equal torque in both directions of the servomotor.

Gain, phase, and balance adjustments are often present in one amplifier. These adjustments tend to interact, so that when one of them is changed it may affect the others. Therefore, after making any one adjustment, it is a good practice to check the other adjustments.

## RESPONSE TIME

Fire control requires a servo system to operate smoothly, rapidly, and with as few errors as possible. To obtain these operational characteristics, one quality is counterbalanced against the other. To increase the rapidity of response of the system to a signal, the gain is increased. This also tends to reduce error in the system. But a high gain or "tight" servo has a tendency to overshoot and oscillate, or, in other words, to be unstable. Response or synchronization time is the time the servo requires to settle down in synchronization to an order signal.

## HUNTING

A servo will drive its load to the correspondence position. The servo's error signal and output torque are zero at correspondence, but because of the load's inertia, it will continue to move. As the correspondence point is passed, the error signal tends to reverse the direction of movement. But, a short time is needed to stop the load; and, during this time, the load will continue to move away from correspondence. When it does stop, the error signal will drive the load back towards correspondence. At correspondence the load has again acquired sufficient inertia to drive on past. The result is a series of overtravels of the correspondence point (fig. 1-31).

This condition is called *hunting*, and it is a characteristic that must be corrected in all servos. Obviously, hunting reduces the smoothness of the servo's follow-up action and increases its synchronization time. To overcome hunting, the servo must anticipate the load's inertia and its position with respect to the correspondence point.

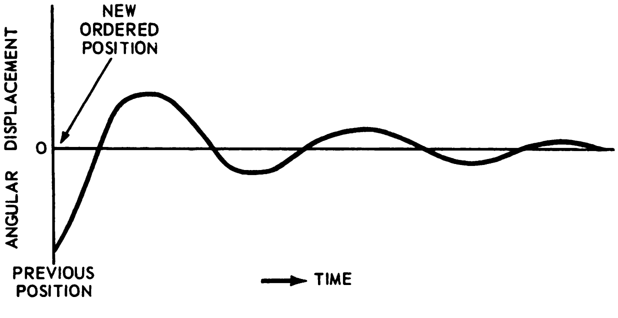

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Figure 1-31.—Overtravels of the correspondence point.

When a servo is hunting, its oscillations about the correspondence are of a low frequency. A servo with a high gain amplifer has a tendency to oscillate at a high frequency with a low amplitude. The high frequency oscillations are started by some type of disturbance or variation, such as random noise in the electrical section of the servo or lost motion in the mechanical section. Once the oscillations are started, the high gain of the amplifier tends to assist them while the inertia of the load continues to reintroduce the error caused by the oscillation.

## STABILIZATION THROUGH DAMPING

To obtain smoothness of operation, the system's gain is damped. Damping can be obtained by either introducing a voltage in opposition to the signal voltage or placing a physical restraint on the servo output. The function of *damping* is to reduce the amplitude and duration of the oscillations that may exist in the system. Every system has one or more natural oscillating frequencies, which depend on the weight of the load, designed speed, and other characteristics.

The degree of damping is determined by the required operating characteristics of the servo system. If the system is OVERDAMPED, it will not oscillate about the correspondence point. However, because of the large amount of restraint placed on the servo, it will have a comparatively large dead-space or steady-state error. The overdamped servo will also take an excessively long time to synchronize (fig. 1-32).

On the other hand, the UNDERDAMPED servo system can respond instantly to an error signal. But it will operate erratically because of the low amount of restraining force placed on the servo, and it will oscillate about the point of synchronism. Somewhere between these two extremes, we can obtain adequate accuracy and smoothness plus a moderately short synchronizing time.

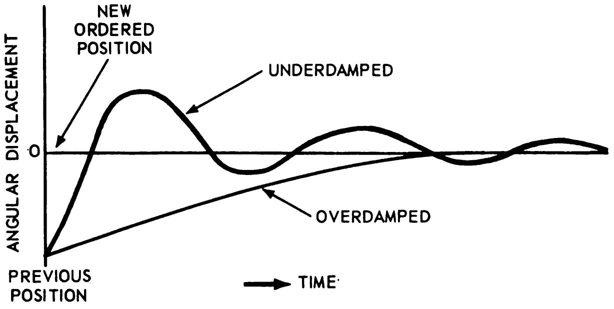

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Figure 1-32.—Degree of damping.

### Viscous Damping

The simplest form of damping is *viscous damping*. This is the application of friction to the output shaft or load that is proportional to the output velocity. The amount of friction applied to the system is critical, and it will materially affect the results of the system. The application of friction absorbs power from the motor, and this power is dissipated in the form of heat.

A pure viscous damper would absorb an excessive amount of power from the system. However, a system having some of the characteristics of a viscous damper, but with somewhat less power loss, is used in actual practice. The first damper of this type to be discussed uses a friction clutch to couple a weighted flywheel to the output drive shaft. A flywheel has the property of inertia.

**FRICTION CLUTCH.**—As the servomotor rotates, the clutch will couple a definite amount of this motion to the flywheel. The flywheel will gradually overcome its inertia and gain speed until it approaches the velocity of the motor. The flywheel, in turning, absorbs energy (power) from the servomotor. The amount of energy stored in the flywheel is determined by its velocity. Because of inertia, the flywheel will resist any attempt to change its velocity.

As the point of correspondence is neared and the error signal is reduced, the motor starts to slow down. The flywheel immediately releases some of its energy into the output shaft in an attempt to continue at the same speed. Thus, the flywheel will cause a large first overtravel. The servo system, to correct for this overtravel, reverses the direction of the motor. Once again the flywheel resists the motor movement and absorbs energy from the system. This drastically reduces the second overtravel and all subsequent overtravels of the motor. This effect dampens the oscillations about the point of correspondence and reduces the servo system's synchronizing time.

The motor rotation is transmitted to the flywheel through the friction clutch. The inertia of the flywheel is an additional load on the motor. The friction clutch will slip with any rapid change of direction or speed. This slipping effectively disconnects the flywheel instantaneously, and thus governs the amount of power the flywheel will draw from the motor.

**MAGNETIC CLUTCH.**—Another type of viscous damper is the MAGNETIC or EDDY CURRENT damper. The magnetic damper is functionally similar to the friction clutch damper. The principal difference between the two is in the method of coupling the flywheel (inertia weight) to the servomotor output shaft. In the magnetic damper, the shaft and flywheel are coupled by a magnetic field, rather than a frictional contact. The coupling is made by the interaction of a magnetic field generated by a permanent magnet that rotates with the rotor of the servomotor and the induced eddy current in the flywheel.

The effect of viscous damping is shown in figure 1-33. The solid line shows the action of

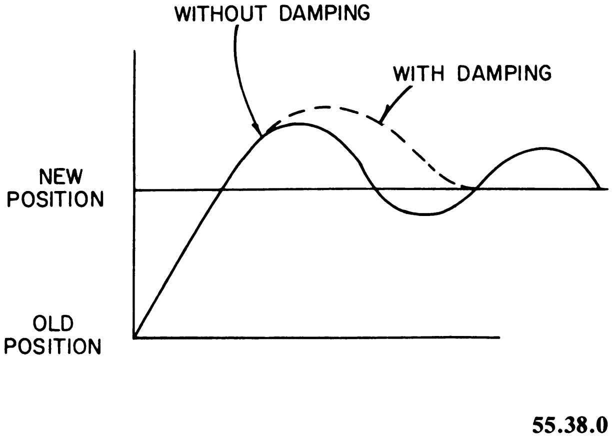

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Figure 1-33.—Effect of friction damper.

the load without damping. The time required to reach a steady-state condition should be noted. This time is greatly reduced with damping, although the initial overshoot is increased. Viscous dampers effectively reduce transient oscillations, but they also produce an undesirable steady-state error (velocity lag or position error). Since the friction damper absorbs power from the system, its use is normally limited to small servomechanisms.

### Error-Rate Damping

Since no physical device can respond instantaneously to a sudden force, there is a time lag between the signal input of a servo system and its output response. To reduce this time lag, amplification is increased. We know that this also accentuates the tendency of the system toward instability. Viscous dampers act as part of the servo load, so they are not the answers to reducing the response lag. The answer lies in increased amplification with error-rate damping.

Error-rate damping consists of introducing a voltage that is proportional to the rate of change of the error signal. This voltage is combined with the error signal in the proper ratio to obtain optimum servo operation with negligible overshooting and oscillations.

The advantages of error-rate damping are as follows:

- Maximum damping occurs when a maximum rate of change of error signal is present. This normally occurs when the servo load reverses direction. Obviously, this is when maximum damping action is required.

- Since a CHANGE in the signal causes damping, there is a minimum amount of damping when no signal, or a signal of constant strength, is present. This means small steady-state errors.

Error-rate voltages are generated by either electromechanical devices or electrical networks in fire control equipment. An electromechanical device widely used to generate an error-rate voltage is the tachometer generator. The tach is mechanically coupled to, and rotates with, the servo's output shaft. Its output voltage is proportional to the output velocity of the servo. Since the voltage output is proportional to load velocity, it is also proportional to the inertia of the load due to its velocity. Hence, the output voltage can be fed back to the amplifier to indicate the load's velocity, and, therefore, its inertia.

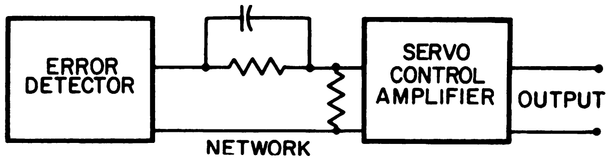

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Figure 1-34.—Error rate stabilization network.

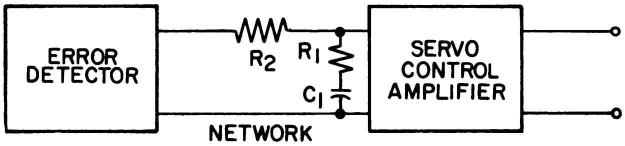

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Figure 1-35.—Integrator used as an integral stabilization network.

Electrical networks used for error-rate damping consist of a combination of resistors and capacitors forming an RC differentiating network. From your study of basic electricity, you know that a differentiating circuit produces an output voltage that is proportional to the rate of change of the input voltage. In an RC circuit, if the voltage across the resistor is used as the output, it is referred to as a DIFFERENTIATOR (fig. 1-34), and if the voltage across the capacitor is the output, it is referred to as an INTEGRATOR (fig. 1-35).

Servos used in fire control equipment are required to follow an input signal, which is sometimes changing at a constant rate and sometimes at a variable rate. A director's train power drive is an example of a servo whose input signal may be fixed, changing at a constant rate, or at a variable rate. When the director is tracking a target on a steady course and speed, the train rate may be constant. However, if the target changes course or speed, the director train drive may require a sudden acceleration. It can be seen that this servo must adapt itself to a variety of signals, and respond to them with substantially zero error.

Let's use the integrator circuit shown in figure 1-35, or, as it is sometimes called, an integral control to explain error-rate damping. The integral control circuit is shown in its simplest form. It is made up of a combination of two resistors and a capacitor. Notice that the network is in series with the error detector and the amplifier. The circuit is designed for dc signals. If the error detector puts out an ac signal, it must be demodulated before it enters the network. The signal is dropped across $R_2$ and the $R_1$, $C_1$ leg of the network. The $R_1$, $C_1$ leg is in parallel with the amplifier's input circuit. Therefore, only that portion of the signal developed across the $R_1$, $C_1$ leg is fed into the amplifier. $R_2$ is in series with the leg and is larger than $R_1$. Briefly, here is how the circuit works.

Assume that the error signal is steady or changing slowly. Initially, all of the constant error voltage is divided between $R_1$ and $R_2$. But the longer the error voltage is applied, the more $C_1$ charges up. The increasing voltage drop across $C_1$ adds to the drop across $R_1$. Since these two components are in parallel with the amplifier, their combined voltages will appear at the input terminals of the amplifier. In effect, the servo will overcorrect the error signal and the output shaft will catch up with the input signal. As the drive increases its velocity, it will reduce the error signal. The capacitor $C_1$ will start to discharge and oppose the reduction. The damping action of the capacitor's charging and discharging voltages, which oppose the changes in the error signal, assists the servo to settle down quickly at the new velocity.

The discussion of an integral control is by no means complete. There are many types of RC circuits and many different applications of their use for error-rate damping in servos. The discussion does cover the fundamental operation of an electrical RC network, which can provide error-rate damping.

## FREQUENCY RESPONSE

At first, we considered the order as being suddenly put at a fixed value. Later, we studied the case where the order slowly increased in value, where it was constantly moving. Actually, the order to a servo may accelerate, start, stop, or oscillate about a fixed point. We will now consider actions of a servo while the order oscillates. When the order is constant, oscillations of the load are undesirable. When the order oscillates, the load must oscillate in a similar manner.

### Meaning of Frequency Response

The *frequency response* of a servo depends upon the range of frequencies over which the order may oscillate and still produce similar oscillations in the load.

Assume that an oscillating order is put into a servo. The load may behave in several ways. Ideally, it would oscillate at the same frequency, amplitude, and phase as the order. Actually, the amplitude and phase of the load are different from those of the order (fig. 1-36). The frequency is usually the same as that of the order.

A servo may follow the order in amplitude and differ in phase; it may follow the order in phase and differ in amplitude; or it may differ in both phase and amplitude.

### Effect of Gain and Damping on Frequency Response

The higher the frequency of the order, the more difficult it is for a servo to accurately

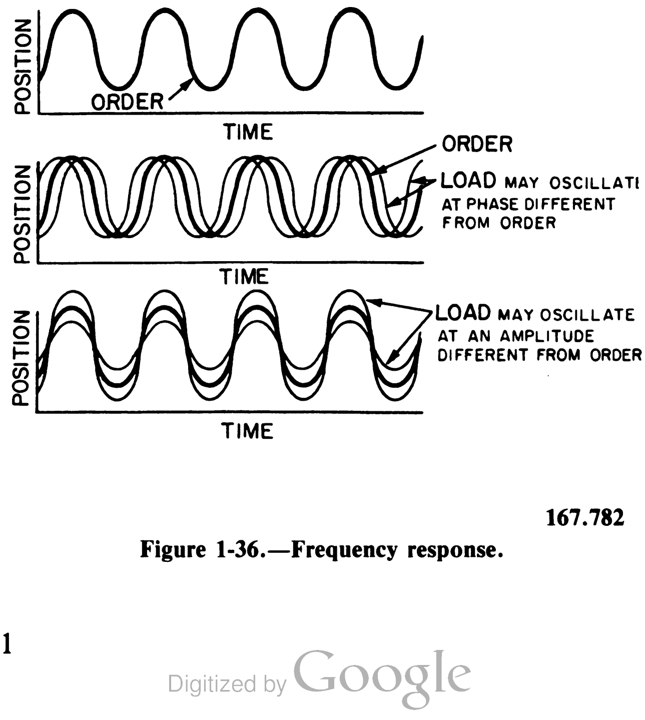

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Figure 1-36.—Frequency response.

follow it. Damping and gain affect frequency response similarly to the way they affect lag. High gain and low damping improve the frequency response.

Frequency response is a good way of judging servo performance, because good frequency response involves a balance of damping and gain, so that maximum stability and least lag are attained. If a servo responds accurately to a wide range of frequencies, it has a correct balance between damping and gain.

Assume that a high-frequency order is being put into the servo. If the servo has high gain and low damping, the rapidly increasing error at the beginning of the ordered motion would cause the load to leap to a response, and it would catch up to the order. However, when the order reverses direction, low damping and high gain would cause the load to overshoot, as shown in figure 1-37.

If the servo has low gain and high damping, the load would move slowly while the order changed rapidly, causing a large lag. However, when the order changes direction, the low gain will cause little overshoot, as shown in figure 1-38.

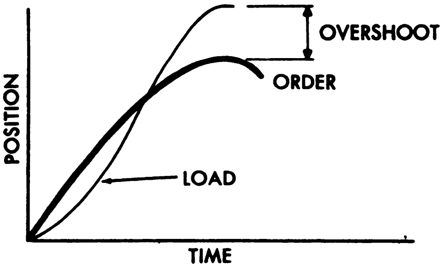

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Figure 1-37.—High gain, low damping.

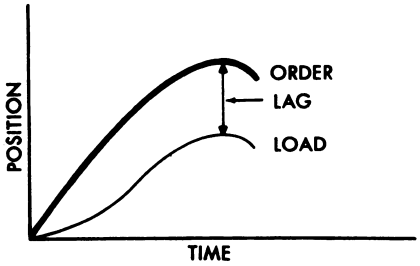

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Figure 1-38.—Low gain, high damping.

## SUMMARY

This chapter has provided information basic to understanding servo systems and their components. The following is a summary of specific points in the chapter.

THE OPEN-LOOP CONTROL SYSTEM is controlled directly and only by an input signal. It has no feedback and is, therefore, less accurate than the closed-loop control system. The open-loop system usually requires an operator to control the speed and direction of movement of the output.

THE CLOSED-LOOP CONTROL SYSTEM is the most common type of system used in the Navy. It can respond and move loads quickly and with greater accuracy than the open-loop system. The closed-loop system has an automatic feedback system that informs the input that the desired movement has taken place.

THE SERVO SYSTEM is classified as a closed-loop system when it is capable of the following:

1. Accepting an order and defining the desired result
2. Evaluating present conditions
3. Comparing the desired result with present conditions and obtaining a difference or an error signal
4. Issuing a correcting order, and changing the existing conditions to the desired result
5. Obeying the correcting order

THE BASIC SERVO SYSTEM is normally made up of electromechanical parts, consisting of a synchro-control system, servo amplifier, servomotor, and some form of feedback.

THE POSITION SERVO has the goal of controlling the position of the load. In the ac position servo system, the amplitude and phase of the ac error signal determine the amount and direction the load will be driven.

In the dc position servo system, the amplitude and polarity of the dc error signal are used to determine the amount and direction the load will be driven.

THE VELOCITY SERVO is based on the same principle of error-signal generation as the position servo except the VELOCITY of the output is sensed rather than position of the load. When the velocity loop is at correspondence, an error signal is still present, and the load is moving at the desired velocity.

THE ACCELERATION SERVO is similar to the velocity and position servos except that the acceleration of the load is being sensed rather than the position or velocity. In this loop, the tachometer of the velocity loop is replaced with an accelerometer.

TIME LAG is the time it takes between the input signal and actual movement of the load. Time lag is undesirable and is reduced through the use of high-gain amplifiers. Damping systems are then added to attain smooth, efficient operation.

An OVERDAMPED system is not subject to oscillations, but it takes an excessive amount of time to reach synchronization. An UNDERDAMPED system has the favorable trait of instant response to an error signal, but it results in the load oscillating about the point of synchronism. Somewhere between overdamped and underdamped, designers achieve adequate accuracy, smoothness, and a moderately short synchronizing time.

DAMPING is used to stabilize a system and to minimize or eliminate the problem of overshoot. The simplest form of damping is FRICTION CLUTCH damping. MAGNETIC CLUTCH damping is similar to friction clutch damping. The difference is in how the flywheel is coupled to the shaft of the servomotor. Magnetic coupling uses a magnetic field to draw two friction plates together to produce damping. Another method uses the magnetic field set up by a pair of coils or one coil with a conducting surface (flywheel) to produce damping.

ERROR-RATE DAMPING is defined as a method of damping that "anticipates" the amount of overshoot. This form of damping corrects the overshoot by introducing a voltage in the error detector that is proportional to the rate of change of the error signal. The stabilization network used for error-rate damping consists of either an RC differentiating or an integrating network. The components of the RC network are chosen to tailor the stabilization network to the requirements of the servo system.

FREQUENCY RESPONSE of a servo is that range of frequencies to which the system is able to respond in moving the load. The ideal system is able to respond to whatever frequencies are present in the input signal. Frequency response is a good way of judging servo performance. In a given servo system, good frequency response provides maximum stability and minimum time lag.

MODULATORS are used to change a dc error signal into an ac input error signal for servo amplifiers. This device is required when ac servo amplifiers are used instead of dc amplifiers.

DEMODULATORS convert ac error signals to dc error signals. The dc signal is required to drive a dc servo amplifier.

A SERVO AMPLIFIER used in an ac or dc servo system must have a flat gain, minimum phase shift, low output impedance, and low noise level.

AC SERVOMOTORS are used in servo systems that move light loads. Large ac motors are too inefficient for servo use when large loads are to be moved.

DC SERVOMOTORS can control heavy loads and are widely used in servo systems. The speed and direction of the dc servomotor can be varied easily by varying the armature current.

MAGNETIC AMPLIFIERS are used when power from a conventional servo amplifier is too small to drive large servomotors (either ac or dc).

AMPLIDYNE DRIVE is a rotary amplifier capable of producing high current gain to enable heavy dc motor operation.

Now that you should be familiar with servomechanisms, we will move on to analog computers in the next chapter. Analog computers in various configurations use servo systems. Other chapters later in this RTM will also make use of servo systems, such as the search and fire control radars discussed in chapter 4.

## CHAPTER 2

# ANALOG COMPUTING ELEMENTS

There are two distinct branches of the computer family. One branch is descended from the abacus, a mechanical extension of the idea of finger (digit) counting. It uses digits in the form of pulses and the absence of pulses to express numbers; therefore, it is called a digital computer. In other words, it simply counts. The other member of the family, the ANALOG computer, measures some continuous quantity such as the value of a voltage. The measured voltage represents, or is analogous to, some quantity such as distance, speed, angle, weight, and time.

Computers are classified by how they calculate. Digital and analog computers can also be classified physically and functionally. Physically, computers are classified as mechanical, electronic, and electromechanical. The classification of an analog computer is determined by the type of devices used in its construction. Analog computers are composed of computing devices that can be scaled to represent quantities: mechanical, electromechanical, or electronic.

The mechanical category includes differentials, linkages, cams, slides, multipliers, and component solvers. If you want to broaden your knowledge of the computer field, you will find a description of these elements in *Basic Machines*, NAVPERS 10624A.

In the electromechanical type of analog computer, problems are solved by using combinations of electrical signals and mechanical motions; for example, synchros, potentiometers, and resolvers. Data converters and coordinate converters are analog computers with names that reflect their function.

Functionally, there are as many types of computers as there are problems; for example, the coordinate converter, the data converter, the ballistic computer, and the steering computer.

In the electronic computer, mathematical processes are solved by using voltages only; for example, amplifiers, summing networks, and differentiating and integrating circuits.

Analog computers make use of the following electrical computing elements:

- Amplifiers
- Networks for addition and subtraction
- Resolvers for resolving a vector into its two components, for solution of right triangles and coordinate rotation
- Potentiometers for multiplication
- Function potentiometers and networks for generation of nonlinear functions.

Many analog computers are still used, even though the Navy has been steadily converting fire control and weapons systems to digital systems since the mid 60s. There are still many devices in digital systems that perform analog computing functions. These devices may not be grouped together and called an analog computer, but they are still performing analog computing functions. These analog devices are found in radars, display systems, analog to digital (A/D) converters, digital to analog (D/A) converters, servo systems, and many other areas. Originally, these computing elements were mechanical or electromechanical. Now, they are solid state electronic circuits and perform the same functions. As a Fire Controlman, you should become very familiar with analog computing elements as well as digital. Now, we will study analog computers and computing elements.

An analog computer simulates a mathematical problem in a physical system. In fire control computers, the mathematical problem is duplicated using mechanical, electrical, and electronic computing circuits or components. The physical values in these systems are measurable. As an example, we will use the computation for future target height Rv2. The formula for Rv2 is

$$Rv2 = (R \sin E) + (T2 \cdot DMv)$$

Where

$R$ = present range

$E$ = present elevation

$T2$ = time of flight

$DMv$ = linear rate at which target height is changing

Solving the formula requires four separate operations:

1. Find sin E
2. Multiply sin E by R
3. Multiply T2 by DMv
4. Add R sin E and T2 DMv

In figure 2-1 these operations are shown in an arrangement similar to that found in a computer. The mathematical functions are shown in block form. By substituting computing elements, we can mechanize the formula. R and E are measured by the director, and are known quantities. T2 and DMv are computed quantities that we will assume are correct, for they enter the formula with definite values.

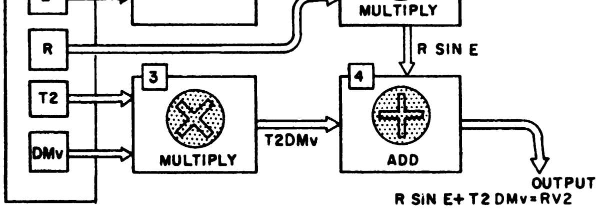

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Figure 2-1.—Mathematical operations.

Each element in the figure solves a discrete problem that is an integral part of the overall problem. There is practically no delay in an element arriving at an answer; once its inputs are set, the answer is present as an output. The input values of R and E are represented by a voltage and an angle, respectively. An infinite number of combinations of these values are possible, but they can be represented quickly and accurately in their analogous systems. As a target moves in or out along the range scale, its voltage representation follows it in a linear manner along the voltage scale. The voltage, within its limits of operation, is a continuous, uninterrupted representation of the numerical value of range. Thus, although we have two dynamic input quantities, the answer is always available.

## SCALE FACTORS

At one time or another, you have probably used a road map to estimate the distance from one point to another. Usually, at the lower edge of the map, there is a scale that is graduated in miles/inch. This ratio is called a scale factor. It states the ratio of the scaled drawing to the actual area that the map represents. By measuring the distance between points in inches and multiplying this number by the miles/inch, obtained from the scale, you get an estimate of the number of miles between points.

Another familiar example of a scale factor is the mileage indicator in an automobile. Here, during design, the engineer determines how far the car will move for one revolution of the drive shaft, then connects a counter to it, and scales the counter to represent the distance the car is driven. In reality, all the counter is doing is counting the drive shaft revolutions. Here, the scale factor is the ratio of the distance covered to one revolution of the drive shaft.

Just as the inches on a road map and the revolutions of the drive shaft are used as scaled factors to represent some physical knowledge, the elements of an analog computer are scaled to represent physical quantities within the computer.

## SCALE FACTORS IN ANALOG COMPUTERS

A *scale factor*, selected for use in an analog computer, is a constant that relates a computer variable directly to a variable of the problem being solved. In other words, it is the ratio of the *analog units* to the *equation units*. Thus,

$$\text{Scale Factor} = \frac{\text{Analog Units}}{\text{Equation Units}}$$

The most commonly encountered *analog units* are volts and shaft revolutions. These analog units are used to represent the physical variables (or *equation units*) of the fire control problem, such as range, elevation, bearing, speed, initial velocity, and many others. The larger the scale factor, the more accurate the results will be; or, the larger the ratio of analog units to equation units, the more accurate the results. When the statement is applied to scale factors in an analog computer, it can be illustrated as shown in the following examples:

Example 1: If one revolution of a shaft represents 360°, the shaft has a smaller scale factor than one that is representing 10°.

$$\text{Scale factor} = \frac{\text{Analog Units}}{\text{Equation Units}}$$

$$\text{Scale factor} = \frac{1\ \text{Rev}}{360^\circ}$$

$$\text{Scale factor} = 0.00277\ \text{Rev/Deg.}$$

$$\text{Scale factor} = \frac{\text{Analog Units}}{\text{Equation Units}}$$

$$\text{Scale factor} = \frac{1\ \text{Rev}}{10^\circ}$$

$$\text{Scale factor} = 0.1\ \text{Rev/Deg.}$$

Since 0.00277 is less than 0.1, the scale factor for a shaft representing 360° is smaller than for one representing 10°.

Example 2: If 1 volt represents a distance of 100 yards, the scale factor is larger than when 1 volt represents 1,000 yards.

$$\text{Scale factor} = \frac{\text{Analog Units}}{\text{Equation Units}}$$

$$\text{Scale factor} = \frac{1\ \text{Volt}}{100\ \text{Yards}}$$

$$\text{Scale factor} = 0.01$$

$$\text{Scale factor} = \frac{\text{Analog Units}}{\text{Equation Units}}$$

$$\text{Scale factor} = \frac{1\ \text{Volt}}{1{,}000\ \text{Yards}}$$

$$\text{Scale factor} = 0.001$$

Since 0.01 is larger than 0.001, the scale factor for 1 volt representing 100 yards is larger than when 1 volt represents 1,000 yards.

The actual scale factor used in analog computers depends upon the voltage suitable for the computer circuits. In most computers, a variable in an equation is represented by as large an electrical or mechanical quantity as possible. This gives a larger analog unit to equation unit ratio, thereby increasing accuracy.

When the terms *large scale factor* and *small scale factor* are used in later discussions, you should have a clear concept of their meaning.

## CHOICE OF SCALE FACTORS

In electronic elements, circuit noise affects the values. Also, the saturation point of amplifiers limits the scale values. Furthermore, if the scale factor is too large, the size of the resistors, condensers, and other components in the circuit would have to be increased to handle the increased power required. This would also create a problem of heat dissipation.

The problem of selecting a scale factor for electronic elements is illustrated by the following examples: For a scale factor of 1 volt/4,000 yards, one millivolt (average) of noise in the circuit represents an error of only 4 yards. But with a scale factor of 1 volt/12,000 yards, a millivolt (average) of noise causes an error of 12 yards. Thus, with a small scale factor, a given amount of noise represents a greater error.

On the other hand, if a very large scale factor, such as 1 volt/yard, is used, the problem of handling large voltages is encountered. If the computer had to handle 100,000 yards with a scale of 1 volt/yard, the amplifiers and power sources would have to handle and supply 100,000 volts. This is nearly impossible.

Because of their low noise level, transistors are used extensively in computers. Small scale factors of 1 volt to 8,000 or more yards are common in transistorized analog computers.

## SCALE FACTOR ANALYSIS

You should have a clear concept of scale factors, analog units, equation units, and their relationship to each other.

Given: The maximum range of a computer is 240,000 yards; the maximum voltage that the amplifiers can handle is 12 volts. The scale factor is then equal to:

$$\text{Scale factor} = \frac{\text{Analog units}}{\text{Equation units}}$$

$$\text{Scale factor} = \frac{12 \text{ volts}}{240{,}000 \text{ yards}}$$

$$\text{Scale factor} = \frac{1 \text{ volt}}{20{,}000 \text{ yards}}$$

This scale factor states that 1 volt is equal to, or represents, 20,000 yards.

If the scale factor and the analog units are known, the equation units may be found as follows: (assuming an analog voltage of 3 volts).

$$\text{Equation units} = \frac{\text{Analog units}}{\text{Scale factor}}$$

$$\text{Equation units} = 3 \text{ volts}/\frac{1 \text{ volt}}{20{,}000 \text{ yards}}$$

$$\text{Equation units} = 3 \times \frac{20{,}000 \text{ yds}}{1} = 60{,}000 \text{ yards}$$

If the scale factor and the equation units are known, the analog units may be found as follows:

$$\text{Analog units} = \text{Equation units} \times \text{scale factor}$$

$$\text{Analog units} = 60{,}000 \text{ yds} \times \frac{1 \text{ volt}}{20{,}000 \text{ yds}}$$

$$\text{Analog units} = 3 \times 1 \text{ volt} = 3 \text{ volts}$$

In the maintenance of a computer, it is sometimes necessary to perform the above computations to check the scale factor, the accuracy of the analog voltage, and the overall accuracy of the computation. For some computers, the scale factor is listed at the top of each column for the various computing accuracy tests performed on the computer. For other computers, it is necessary to use the computer prints to obtain the scale factor. In many instances, you will find that the scale factor is expressed as a ratio of equation units to analog units; for example, 90,000 yards/volt or 6,000 yards/rev. Don't let this confuse you. Both methods are accepted forms of expressing scale factors. However, when the scale factor is expressed in equation units/analog units (yards/volt), the smaller the scale factor, the greater the accuracy.

## ELECTROMECHANICAL COMPUTING ELEMENTS

An electromechanical computing element is one that has electrical parts as well as moving parts. Such basic elements as synchros, linear and nonlinear potentiometers, sine and cosine potentiometers, resolvers, and ac and dc generators are included in this category. Except for generators, you have been introduced to all these elements in previous chapters and in the basic training courses. Since the application of all these devices is a universal feature in Navy analog computers, these devices are covered here in more detail.

In an analog computer, these elements perform mathematical operations. The elements are then interconnected to solve equations. In each electromechanical computing element and throughout the computer, a physical quantity, termed the computer variable, represents, or is analogous to, the problem variable.

In a computer using electromechanical computation there are two types of analog variables—voltages and mechanical displacement (shaft revolutions). These variables represent such physical variables as range, elevation, bearing, speed, and initial velocity. Voltages, rather than currents, are used almost exclusively as the computing variable in modern analog computers using electrical computation, because voltages can be measured and recorded at any point in the circuit without disturbing (opening) the circuit. Therefore, electromechanical computing elements convert mechanical displacements into voltages, and appropriate scale factors are assigned to these voltages.

## POTENTIOMETERS

*Potentiometers*, often called *pots*, are the basic components used in analog computers to convert shaft positions to electrical voltages. In this conversion, the pot actually multiplies the constant input voltage by the mechanical position of the slider. Pots are used extensively to multiply, divide, and generate nonlinear functions (sine, cosine, secant, and so forth).

A pot, shown schematically in figure 2-2, view A, is a resistance element having terminals at each end and a sliding contact. The contact traverses the element from one end to the other, varying the resistance between the sliding contact and one of the fixed terminals. Each terminal and the slider are numbered; the slider usually has the higher number. The resistance element of a precision pot is wire wound because wire has a lower noise level than carbon compound or similar mixture.

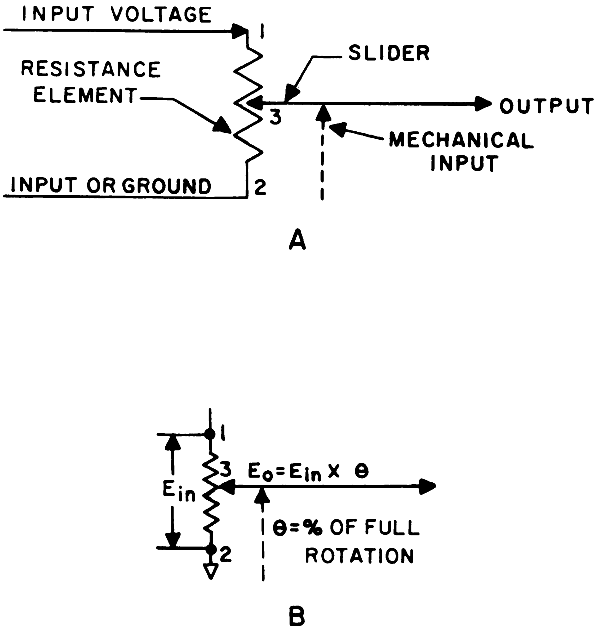

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**Figure 2-2.—A. Potentiometer schematic; B. Volts × motion multiplication.**

The resistance element is wound on a core called a *mandrel*, the shape of which depends on the design and function of the potentiometer. For a linear 1-turn pot, the wire is evenly spaced on the mandrel, which is then shaped to form a circle. This permits the slider to move mechanically through 360° of rotation; thus, the electrical resistance between the slider and one end of the pot varies directly with the mechanical position of the slider. For a linear 10-turn pot, the wire is usually wound on a rod, which is then shaped to form a helix or spiral. This allows the slider to rotate as many as 10 full revolutions. If 360° rotation of the slider is not required, the resistance element may be wound on a rectangular card. However, this type of pot is usually used as a control device rather than as a precision computing pot.

### Types of Potentiometers

There are two types of pots used in analog computers—linear and nonlinear. A linear pot has its resistance element distributed evenly about its mandrel, so that each turn has the same amount of resistance. As the input shaft is rotated, the slider touches various windings and causes a change in resistance between the slider and the ends of the pot. With the pot energized, the voltage output varies linearly as the slider is moved from end to end because the voltage drop across each turn is the same.

A nonlinear pot is one whose voltage output does not vary at a constant rate as the slider moves. Nonlinear pots are sometimes referred to as shaped or tapered pots because the resistance element is wound on specially shaped mandrels, each turn having a different length of wire. Thus, the total resistance is distributed unevenly throughout the length of the pot. With the pot energized, the voltage output varies in a nonlinear fashion as the slider is moved from one end to the other. Nonlinear pots can be constructed to produce practically any of the nonlinear functions present in the weapon control problem.

## Representing Computing Variables Electrically

A potentiometer can also be thought of as a variable voltage source rather than a variable resistor, since the input voltage is applied to the resistance element and a fraction of the voltage appears as the output between the slider and one end of the pot. When the input voltage is constant, the potentiometer converts a mechanical input quantity into an electrical quantity. Thus, any computer variable can be represented electrically by using a pot to make the mechanical to electrical conversion.

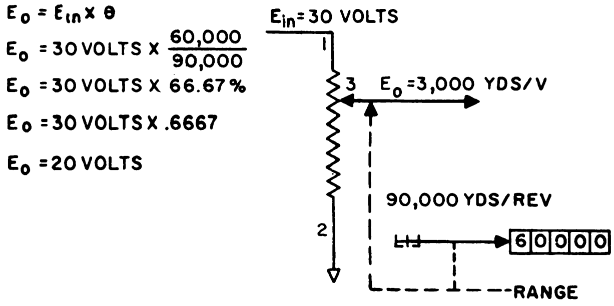
Here, the pot actually multiplies a voltage by a motion (slider position). The input voltage, $E_{in}$, is impressed across the resistance element through terminals 1 and 2. See figure 2-2, view B. The mechanical input, $\theta$ (THETA), is a percentage of full rotation of the slider. If the input voltage is 30 volts and the slider is positioned at 100% full rotation, then $E_o = 30 \text{ volts} \times (1.0) = 30$ volts.

When $\theta$ is at 25% full rotation, only one-fourth of the input voltage occurs at the slider: $E_o = 30 \text{ volts} \times .25 = 7.5$ volts. If $\theta$ is at 50% of full rotation, only one-half of the input voltage occurs at the slider: $E_o = 30 \text{ volts} \times .5 = 15$ volts.

When a suitable scale factor is assigned to the mechanical input, the output can represent any computer variable electrically. For example, assume that a 1-turn potentiometer is used to represent a maximum range of 90,000 yards in a computer. For one full revolution of mechanical input, the slider will move from terminal 2 to terminal 1. This amount of motion represents a range of 90,000 yards. The maximum range, or any fraction thereof, can be represented electrically by positioning the slider between terminals 2 and 1.

When a range counter indicates 60,000 yards, as shown in figure 2-3, the slider has moved through 66.67% of its travel from terminal 2, and 20 volts will appear at the output terminal 3. Thus, by the multiplying feature of the potentiometer (volt × motion), range, represented by a shaft position and indicated by a counter, has been converted into an electrical voltage.

In addition to the mechanical scale factor assigned to a potentiometer, an electrical scale factor is also assigned to the output voltage. The electrical scale factor is the yards/volt ratio. For the problem illustrated, the yards/volt ratio equals


$E_o = E_{in} \times \theta$
$E_o = 30 \text{ VOLTS} \times \frac{60,000}{90,000}$
$E_o = 30 \text{ VOLTS} \times 66.67\%$
$E_o = 30 \text{ VOLTS} \times .6667$
$E_o = 20 \text{ VOLTS}$
$E_{in} = 30$ VOLTS
1
3
$E_o = 3,000$ YDS/V
2
90,000 YDS/REV
6 0 0 0 0
RANGE

167.62

Figure 2-3.—Potentiometer used to represent range electrically (360° rotation).

$$\frac{\text{yards/revolution}}{\text{volts/revolution}} \text{ or } \frac{90,000 \text{ yards}}{30 \text{ volts.}}$$

Thus, the yards/volt ratio is 3,000 yards/volts. This indicates that each volt that appears at the slider represents 3,000 yards of range. Therefore, if 20 volts are measured at the output, and each volt represents 3,000 yards of range, then $E_o = 20 \text{ volts} \times 3,000 \text{ yards/volt} = 60,000$ yards.

Another scale factor pertaining to the potentiometer can be very useful in determining the number of yards an output voltage represents. This scale factor is the ratio of the volts/revolution to the yards/revolution. For the problem illustrated, the volts/yards ratio equals

$$\frac{\text{volts/revolution}}{\text{yards/revolution}} \text{ or } \frac{30 \text{ volts}}{90,000 \text{ yards.}}$$

Thus, the volts/yard ratio is .000333. This scale factor indicates that for each yard inserted into the pot mechanically there will be .000333 volt available at the output. Thus, if the output voltage is 6.666 volts, the number of yards this voltage represents can be determined as follows:

$$\text{Equation units} = \frac{\text{Analog units}}{\text{Scale Factor}}$$

$$\text{Range in yards} = \frac{6,666}{.000333}$$

$$\text{Range in yards} = 20,018.$$

When computing the number of yards an output voltage represents, it is more convenient to use the scale factors of a pot rather than the percentage of full rotation of the slider. This is true because many 1-turn pots actually do not rotate a full revolution. Furthermore, many 10-turn potentiometers only rotate 9.6 revolutions instead of 10 full revolutions. If the pot shown in figure 2-4 is used to represent a maximum range of 90,000 yards electrically, the scale factors assigned indicate that the potentiometer does not rotate a full revolution. If the total yards represented electrically (total yards = applied voltage × electrical scale factor) and the mechanical scale factor are not the same, then the potentiometer does not rotate a full revolution.

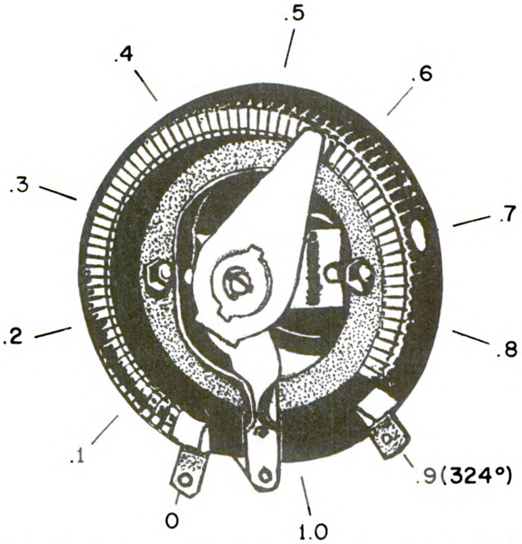
In this problem, the mechanical scale factor indicates that one full revolution of the slider represents 100,000 yards of range. The electrical scale factor and the applied voltage indicate that the maximum range represented electrically is 90,000 yards (30 volts × 3,000 yards/volt). Therefore, a ratio exists between the total yards represented electrically and the yards/revolution. Thus, total revolutions of the pot are equal to

$$\frac{\text{total yards}}{\text{yds/rev}} \text{ or } \frac{90{,}000}{100{,}000} = 0.9 \text{ revolutions.}$$

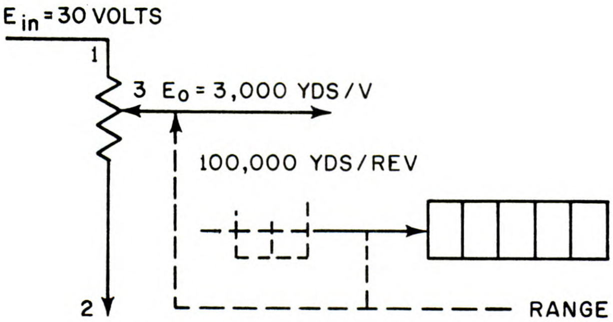
Thus, the pot will actually rotate 324° (360 × 0.9) to represent 90,000 yards of range.

What effect does this amount of rotation have on the volts/revolution, yards/volt, and volt/yard ratio of the pot? Each ratio is compared for both pots to show which is affected.

You can see from table 2-1 that only the volts/revolution ratio is changed. The other



A. MECHANICAL INPUT = DIAL READING X 100,000 YDS



B. ELECTRICAL REPRESENTATION OF (A)

167.63

Figure 2-4.—Potentiometer used to represent range electrically (324° rotation).

Table 2-1.—Volts/Revolution, Yards/Volts, and Volts/Yard Ratio

| RATIO | 90,000 YDS/REV POT | 100,000 YDS/REV POT |
|---|---|---|
| Volts/Rev | $\frac{30 \text{ volts}}{1 \text{ rev}}$ = 30 volts/rev | $\frac{30 \text{ volts}}{.9 \text{ rev}}$ = 33.333 volts/rev |
| Yards/Volt | $\frac{90{,}000}{30}$ = 3,000 yards/volt | $\frac{100{,}000}{33.333}$ = 3,000 yards/volt |
| Volts/Yard | $\frac{30}{90{,}000}$ = .000333 volt/yard | $\frac{33.333}{100{,}000}$ = .000333 volt/yard |

167.746

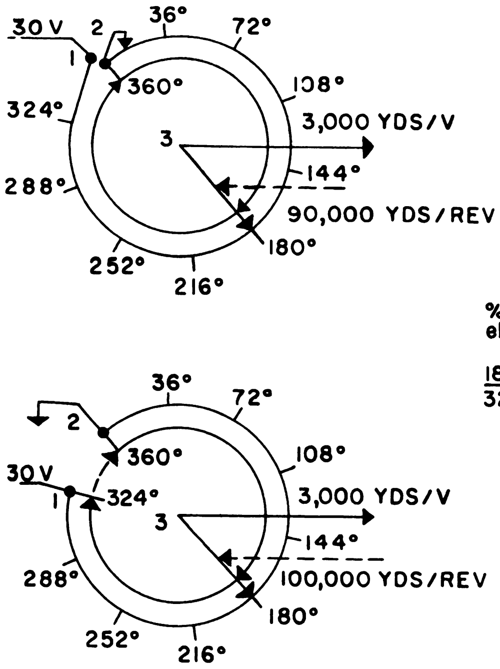
ratios will not change because the electrical scale factor for each pot is 3,000 yards/volt. However, if each pot is rotated the same number of degrees, the percentage of full travel, the output voltage, and the number of yards represented electrically are different for the two pots. In figure 2-5, each slider has been rotated 180° from terminal 2. The percentage of full travel, the output voltage, and the yards represented by each pot are computed for a mechanical input of 180°.

### Double-ended Potentiometers

A potentiometer can be used to represent a variable that may be either plus or minus with respect to a zero reference. In this case, both ends of the pot are energized, one with a plus voltage and the other with a negative voltage. The center of the pot represents the zero reference. The center may or may not be grounded.

When used this way, the pot still multiplies a voltage by slider position. However, when the slider is at the center of the resistance element, the output voltage is zero. Therefore, the center of the pot is the point of reference from which the percentage of rotation is measured. As shown in figure 2-6, the pot is energized with + and − 16 volts and the slider is positioned one-quarter of a revolution from the center (zero reference) of the pot (this amount of slider travel is one-half of the available slider travel from the center to the end of the pot). The output voltage, $E_o$, is computed by multiplying the input voltage, 16 volts, by twice the percentage of rotation of the pot ($E_o = 16 \times 2(0.25) = 8$ volts). The output voltage will be either plus or minus depending on the direction of slider movement from the reference point.

The potentiometer in figure 2-6 electrically represents a rate whose maximum limits are + and − 400 knots; thus, it is possible for the rate



% of full travel of slider on resistance element is:

$\frac{180°}{360°} = .50$ or 50%.

$E_0 = E_{in} \times \theta$

$E_0 = 30v \times .5$

$E_0 = 15$ volts

$E_0$ = in yards is:

15v x 3,000 Yds./V = 45,000 Yds.

% of full travel of slider on resistance element is:

$\frac{180°}{324°} = .55555$ or 55.555 %

$E_0 = E_{in} \times \theta$

$E_0 = 30v \times .55555$

$E_0 = 16.6665'$volts

$E_0$ in yards is:

16.6665 v x 3,000 Yds/V = 50,000 Yds.

167.64

Figure 2-5.—Comparison of potentiometer outputs.

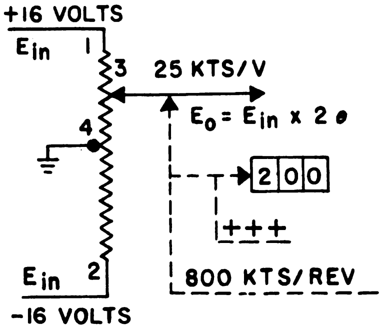


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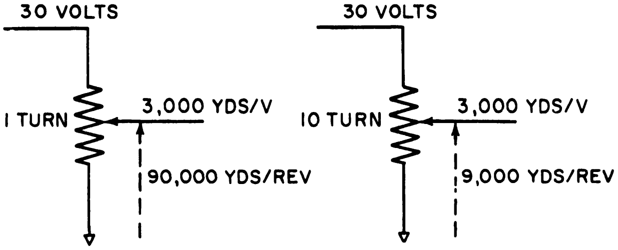
**Figure 2-6.—Potentiometer representing a plus and minus rate.**



167.66

**Figure 2-7.—Using multiturn potentiometers to increase accuracy.**

to change a total of 800 knots (−400 knots to 0 and 0 to +400 knots). The travel of the slider from one end to the other will represent 800 knots, and, if a 1-turn potentiometer is used, the mechanical scale factor must be 800 knots/revolution. The difference in voltage between each end of the 1-turn potentiometer is 32 volts, which represents 800 knots. Therefore, the following ratios can be written for the potentiometer:

$$\text{Volts/Rev} = 32 \text{ volts/revolution}$$

$$\text{Knots/Rev} = 800 \text{ knots/revolution}$$

$$\text{Knots/Volt} = \frac{800 \text{ kts/rev}}{32 \text{ volt/rev}} = 25 \text{ kts/v}$$

$$\text{Volts/Knot} = \frac{32 \text{ volt/rev}}{800 \text{ kts/rev}} = .04 \text{ volt/kt}$$

If the slider is positioned to represent 200 knots, then the output voltage is determined as follows:

Equation units × Scale factor = Analog units. Thus,

200 knots × 0.04 volt/kt = 8 volts.

**Multiturn Potentiometers**

The choice of mechanical scale factors is very important when dealing with pots. You have seen that the mechanical scale factor is always compatible with the physical limits of a pot, and the electrical scale factor represents the mechanical input at all times. The use of multiturn pots increases the accuracy of the mechanical input so that lost motion (number of degrees the slider is in error) does not cause too large an error in the output.

Figure 2-7 shows two pots; they are used to represent 90,000 yards of range. The same electrical scale factor (3,000 yards/volt) is maintained for each. However, to increase the accuracy of the output per degree of error of the slides, one is a 10-turn pot. Each pot is energized by 30 volts. The slider of the 1-turn pot rotates 360° while the 10-turn slider moves through 3,600°. Table 2-2

**Table 2-2.—1-Turn to 10-Turn Potentiometer Accuracy**

| | 1 -TURN POTENTIOMETER | 10 -TURN POTENTIOMETER |
|---|---|---|
| Total Travel | 360 degrees | 3, 600 degrees |
| Yards/Volt | 3, 000 | 3, 000 |
| Yds/Degree | 90, 000 Yds/360° = 250 | 90, 000 Yds/3, 600° = 25 |
| Volts/Degree | 30 volts/360° = . 08333 | 30 volts/3, 600° = . 008333 |
| 1° of error | . 08333 volts or 250 yards | . 008333 volts or 25 yards |

167.747

can be used to compare the accuracy of the 1-turn to 10-turn pots.

### Sine and Cosine Potentiometers

A specially constructed potentiometer can be used to generate voltages proportional to the sine and cosine of a computer variable, which appears as a mechanical rotation. This function generator is called a sine and cosine potentiometer.

The shape of the potentiometer card (fig. 2-8) is made proportional to the cosine function, then the resistance element is wound in a continuous layer around the card. The ends of the card are then joined together, thus forming a cylinder with two lobes. The ends of the resistance element are joined together to provide for continuous rotation of the potentiometer shaft.

The high points, or lobes, of the cylinder are connected to ground. A positive voltage is connected to one of the low points and a negative voltage to the other. The sine and cosine outputs are obtained simultaneously by having two sliders 90° apart and connected mechanically as a single unit but electrically isolated from each other and the potentiometer shaft.

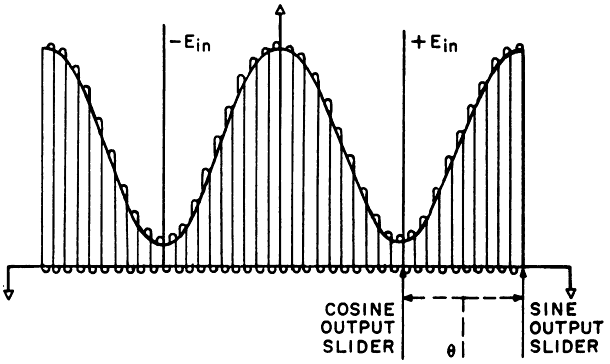
The potentiometer shaft is shown in its zero position. The sine output is zero volts because the slider is in contact with a grounded portion of the resistance element. The cosine output is a maximum plus voltage because the slider is in contact with the plus reference voltage. One full rotation of the shaft counterclockwise reduces voltages that are proportional to the sine and cosine functions of the mechanical input. The polarity of the output voltages is the same as the signs of the sine and cosine functions for all four quadrants.

## RATE GENERATORS

A rate generator (tachometer) (fig. 2-9) puts out a voltage proportional to the magnetic field surrounding the motor and the speed of the rotor. In a rate generator, the magnetic field is held constant but the speed of the rotor is variable. The amplitude or value of the output voltage is proportional to the velocity of the input signal (speed of rotation of the rotor).

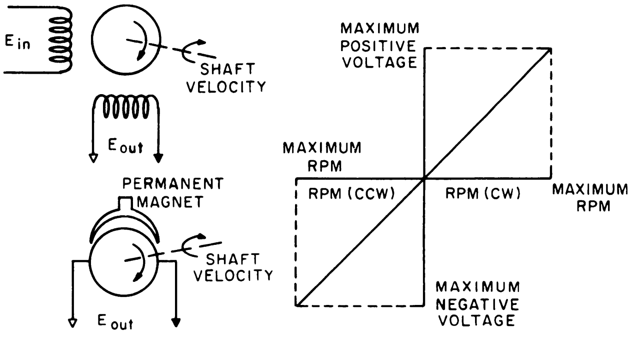
Rate generators are used in computers to perform computations and as a source of stabilizing voltage for servo loops. This is changing mechanical information (speed) to electrical information.

The rate generator used in computers may be an ac or a dc generator. The dc generator uses a permanent magnet to produce the magnetic field. The ac generator is excited by an ac voltage that produces the magnetic field in which the rotor rotates. The flow of energy is from input winding, to rotor, to output winding. The output signal is the same frequency as the excitation voltage and is always 180° out of phase with the input, maintained by a constant direction of rotation. The ac or dc rate generator will theoretically produce a zero output when the rotor is stationary, and it will produce an output voltage



55.3

Figure 2-8.—Sine and cosine potentiometer, cosine card type.



167.88

Figure 2-9.—Output voltage versus RPMs for ac and dc rate generators.

whose amplitude is linearly proportional to rotor speed, up to the saturation limit.

In some computers, the rotor of the ac rate generator is mechanically connected to the rotor of a servomotor. In other computers, the rate generator and the servomotor are one unit; that is, each is a separate element, but they have a common rotor shaft. In either case, the speed of rotation of the servomotor provides the mechanical input to the rate generator. In special cases, where a variation in the ratio of output voltage/revolutions per minute is critical, a temperature compensated rate generator is used.

## ELECTRICAL AND ELECTRONIC COMPUTING ELEMENTS

Electromechanical computing elements convert mechanical computer variables into voltages, which in many instances are algebraically added together. The basic electrical computing element that does this job is the parallel resistor network. Its circuit arrangement is shown in figure 2-10.

### PARALLEL RESISTOR NETWORKS

The parallel resistor networks, called network boxes, have an output that is the algebraic sum of two or more inputs. The network box contains precision resistors and capacitors. The precision resistors are noninductive, wire-wound, and hermetically sealed in a metal can. The resistance of the resistors is normally kept within the 0.02 to 3.0 megohm range. The maximum range is the point above which there would be too great a susceptibility to pickup through inductive coupling between elements. A capacitor is connected across each resistor to compensate for any inductance created by the winding of the resistor. The capacitors are preset and should never be changed. In later illustrations, the capacitors are not shown since they only neutralize the inductance of a resistor.

The resistance can and capacitors are enclosed in a metal box, which is also sealed. The input and output leads are connected to pins mounted on a plug; therefore, the network box is a plug-in module. The output of the network box is always through a coaxial cable. This prevents stray pick-up (noise). The input connections are unshielded pins.

The principle advantage of using parallel resistors for the addition of voltages is simplicity; input signals may all be referred to a common grounded return. Without this feature all of the input sources would have to be electrically isolated from each other.

A network box can electrically produce the algebraic sum of two or more voltages, which are either in phase or 180° out of phase. Consider the circuit, in figure 2-11, where two equal voltages of the same polarity are to be combined. Voltages $E_1$ and $E_2$ are connected in series with resistors $R_1$ and $R_2$ respectively, and terminate at a common junction or node point. The voltage at the node point is not the actual sum of the voltages but is proportional to that sum. In this problem, the sum of the two voltages should be +20 volts; however, only 10 volts appear at the output. If one of the inputs is changed to 20 volts, the output should be 30 volts. But, only 15 volts will appear at the output. For these two examples, only one-half of the sum of the two voltages appears at the output. If a third input resistor were added to the circuit and all three of the input voltages were +10 volts, the output voltage would be +10 volts, or only one-third of the total input voltage. In each case there was a scale change, one-half of the total input for the

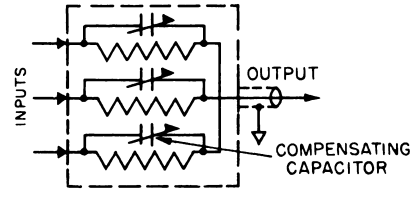


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Figure 2-10.—Parallel resistor network.

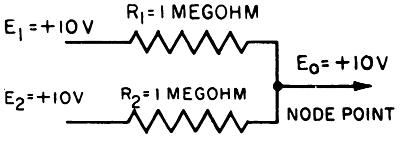

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Figure 2-11.—Parallel resistor summation network.

first two problems and one-third of the total input for the last example. Therefore, the circuit is not always accurate for algebraic addition of analog voltages. Other limitations are as follows:

- Loading at the output changes the effective value of the output impedance and produces a direct scaling error.
- A scaling error is introduced if the number of input sources is changed.
- Each of the input impedances, $R_1$, $R_2$, and $R_3$, acts as a load on all of the inputs simultaneously. This causes interaction among the input voltages.
- For accuracy, the impedances $R_1$, $R_2$, and $R_3$ should be high compared to the respective input impedances. This often raises the overall impedance level of the circuit to a point where pickup from extraneous sources may become a problem.
- To minimize the effects of interaction among the various inputs, the output voltage should be as close to ground potential as possible. This results in a high attenuation of signal from input to output.
- The accuracy of the parallel addition circuit depends directly upon the stability of the impedances, $R_1$, $R_2$, $R_3$, and so forth. Hence, components must be precise.

---

All of the above points refer to the same idea; a summing amplifier is needed in the circuit to prevent loading and to provide summation of voltages without a scale change, unless desired.

---

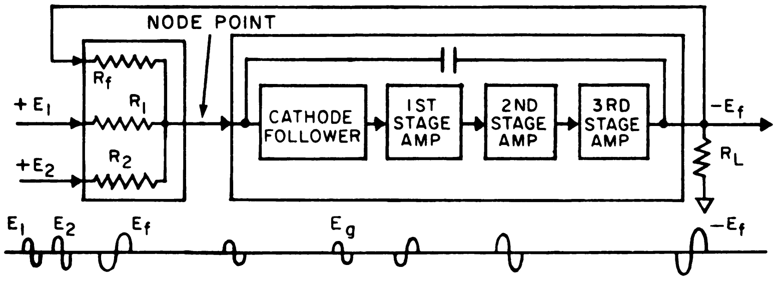
### Summing Amplifier

The summing amplifier (fig. 2-12) used with the network box is also a plug-in module and may use either tubes or transistors. Its components are interconnected by either wiring or printed circuits. Generally, each summing amplifier has three stages of amplification; however, in some special cases it may have five.

When a summing amplifier is in a computing loop, an additional resistor, $R_f$, designated the feedback leg, is required for the negative feedback. The negative output of the amplifier is impressed across the feedback resistor because the amplifier and resistor are in parallel. Therefore, the output of the network box, or node point, is automatically maintained close to ground potential. The summing amplifier actually multiplies the small ac output (Eg) by the amplifier gain factor (u). The amplifier solves the equation, $-Ef = Eg$. The forward gain of the amplifier is high (up to 20,000:1) to ensure accuracy. Negative feedback within the amplifier keeps the gain constant regardless of aging components, and it minimizes harmonic distortion in the amplifier. The amplifier has exactly 180° phase shift from input to output. A capacitor, connected between the input and output, compensates for undesired phase shift.

The summing amplifier features high input impedance and low output impedance. Its output is fed into a resistive load. If the load does not offer the correct resistance, a fixed resistor is connected across the amplifier output to provide the correct load.

Even though the amplifier does amplify its input to produce the feedback voltage, the overall



12.296

Figure 2-12.—Parallel addition circuit using a summing amplifier.

loop amplification is determined by the resistance ratio of the feedback resistor and the input resistors. This will be clarified later.

The summing amplifier does not actually perform any computation other than the multiplication of its input voltage times the amplifier gain. It is always used with network boxes in computing loops. The various computing loops, in which summing amplifiers are used, perform any or all of the following functions:

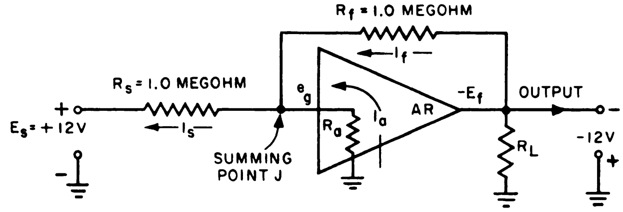


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**Figure 2-13.—Sign reversing loop with unity gain (inverter).**

- Reverse the sign of a voltage, with or without a change in overall loop amplification. Often, it is necessary to change the polarity of a voltage so that a plus and minus voltage is available for the solution of the problem. Also, at times it is necessary to change the overall loop amplification, which in turn changes the scale factor of the output with respect to the input.

- Isolate and/or eliminate loading of one computing element from another. In electrical analog computers, it is necessary to supply extremely accurate voltages from computing elements (potentiometers, sine and cosine pots, and resolvers) to the same or other types of computing elements. If these elements are connected directly, accuracy is lost because of loading.

- Provide a voltage proportional to the algebraic sum of two or more input voltages. Although a summing loop can be considered as a summation of analog voltages, the real job of the loop is to determine the algebraic sum of computer variables. These variables are represented by the analog voltages; hence, scale factors are assigned to each. The computer variables that the voltages represent must have a common reference axis; hence, the input voltages may be in phase or 180° out of phase. Otherwise, an error results.

**Sign Reversing Loop with Unity Gain**

The most basic loop employing a network box and summing amplifier is the sign reversing loop (inverter). The loop reverses the phase of the input voltage and maintains unity gain (1:1). Here is how the loop works. In figure 2-13, $E_s$ and $-E_f$ are the most effective input and output voltages, eg is the amplifier signal voltage; $R_f$ is a fixed resistor located in the network box; and $R_L$ is a fixed load resistor at the output of the amplifier.

If +12 volts is applied to the input leg, current flows from ground through the input impedance of the amplifier, through $R_s$ to the signal source. This current is designated as $I_a$. It causes an input signal (eg) at summing point J, the input to the amplifier. The amplifier amplifies the input signal and provides degenerative (negative or inverse) feedback through $R_f$ to summing point J. From point J, the feedback current flows through $R_s$ to the signal source to ground and back to the amplifier. The feedback current is designated $I_f$. Thus, the current through $R_s$ is $I_s = I_a + I_f$.

If the gain of the amplifier is designated as K, then the output voltage ($E_f$) is K times as large as the input signal voltage (eg). Thus, the output voltage $E_f = -K(eg)$. In this equation, the minus sign before K indicates that there is a 180° phase displacement or sign reversal between eg and $E_f$. This is true because the amplifier has three stages of amplification. The gain of the amplifier is high; assume that it is 10,000 volts. Therefore, the input signal (eg) need be only 1,200 microvolts to attain a maximum value of $-12$ volts for $E_f$ ($1/10{,}000 \times 12 = 0.0012$ volts).

According to Kirchhoff's Law of electrical current, the algebraic sum of the currents entering a junction such as summing point J must be equal to the sum of the currents leaving the junction. Since the amplifier is designed to have practically infinite impedance at the input and between the input and output, the only currents at summing point J are $I_f$ and $I_s$. This equation neglects the very small voltage drop across the input impedance of the amplifier, which will be discussed later. Therefore, the equation can be written $I_s + I_f = 0$. Using this equation, we can solve for the output voltage if we know the values of $R_s$, $R_f$, and $E_s$. Thus, the output voltage of the sign reversing loop is determined as follows:

$$I_s + I_f = 0$$

Rewrite as:

$$I_s = -I_f$$

Substitute Ohm's Law:

$$\frac{E_s}{R_s} = \frac{-E_f}{R_f}$$

Multiplying both sides by Rf:

$$R_f\left(\frac{E_s}{R_s}\right) = -E_f$$

Substitute known values:

$$1.0\left(\frac{12}{1.0}\right) = -E_f$$

Therefore:

$$E_f = -12 \text{ volts}$$

The equation,

$$E_s\left(\frac{R_f}{R_s}\right) = -E_f'$$

expresses the relation between the input and output voltages of the sign reversing loop. The ratio of the output to input voltage is shown to equal the resistance ratio $R_f/R_s$.

If we assigned the $E_s$ input a scale factor of 100 knots/volt, then an input of + 12 volts would represent 1,200 knots. To satisfy a zero, or null condition at summing point J, the feedback voltage must represent − 1,200 knots. We can say, then, there will be a null at summing point J when the inputs (+ 1,200 knots and − 1,200 knots) are balanced. For a + 12-volt input, the current through $R_s$ and $R_f$ is the same; I = E/R = 0.000012 amp. Therefore, this condition produces a zero or null at the input to the amplifier.

### Features Provided by Negative Feedback

As explained in *NEETS MODULE 8*, negative feedback occurs when the amplifier output voltage is fed back to the input out of phase with the input voltage. Negative feedback is also degenerative or inverse feedback. Negative feedback produces several important effects. One effect is to make the gain, or output-input voltage ratio, of the loop much less than the gain of the amplifier. The voltage fed back from the amplifier output opposes the input voltage supplied through the input resistor ($R_s$), thereby reducing the effective signal voltage at the input of the amplifier.

As a result of negative feedback, the loop output-input voltage ratio is practically independent of the amplifier gain. If the amplifier gain should decrease, less voltage would be returned through the feedback path. Less voltage would be available to oppose the input voltage at the amplifier input. Consequently, the signal voltage (eg) would be greater; in fact, sufficiently greater to compensate for the loss of gain.

Another feature gained by negative feedback is an output voltage that is practically independent of output load. An increase in the load tends to reduce the output voltage, but if the output voltage is reduced, less feedback takes place. Less feedback increases the signal voltage (eg) and compensates for the reduction in output voltage. With negative feedback, the effective resistance between the output terminals of the amplifier is less than an ohm. Therefore, any load having a resistance measured in thousands of ohms has small effect.

### Scale Changing (Multiplication and Division)

It is often necessary for the output of a loop to have a different unit/volt ratio than the input. This is referred to as a scale changing.

Consider the loop shown in figure 2-14. The loop's input voltage is +5 volts and each volt represents 100 knots; therefore, the input

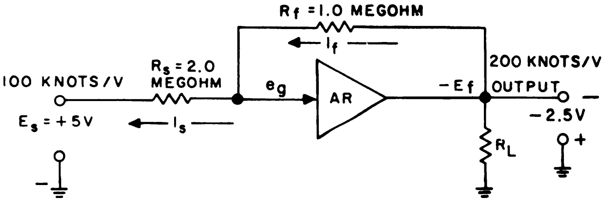

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**Figure 2-14.—Basic circuit for scale changing.**

represents 500 knots. Using the formula previously determined,

$$-E_f = E_s\ (R_f/R_s),$$

the magnitude of the feedback, or output, voltage can be determined. Thus,

$$-E_f = E_s\ (R_f/R_s)$$

$$-E_f = 5(1.0/2.0)$$

$$E_f = -2.5 \text{ volts.}$$

To determine the scale factor of the output voltage, multiply the input scale factor by the resistance ratio of the input leg over the feedback leg (2.0/1.0). Thus,

$$\text{Output scale factor} = \text{Input scale factor } (R_s/R_f)$$

$$\text{Output scale factor} = 100(2.0/1.0) \text{ or } 200 \text{ knots/volt.}$$

Therefore, to satisfy a zero, or null, at the input to the amplifier, only −2.5 volts with a scale factor of 200 knots/volt (−500 knots) are required to balance the input voltage, 5 volts at 100 knots/volt (500 knots).

The zero condition at the input to the amplifier can be seen more clearly if the current through resistors $R_s$ and $R_f$ is considered. If an input of 5 volts is dropped across resistor $R_s$, then the current through the resistor is

$$I_s = \frac{E}{R}$$

$$I_s = \frac{5}{2{,}000{,}000}$$

$$I_s = 0.0000025 \text{ amp.}$$

The current through $R_s$ also flows through the feedback resistor, $R_f$; however, the resistance of this resistor is only 1 megohm. Thus, the voltage across $R_f$ is

$$-E_f = I_f \times R_f$$

$$-E_f = 0.0000025 \times 1{,}000{,}000$$

$$E_f = -2.5 \text{ volts.}$$

Because of the resistance ratio of the feedback leg to the input leg ($R_f/R_s$), the output of the amplifier is only −2.5 volts to provide a null at the input of the amplifier. Thus, the scale factor of the input voltage has been changed from 5 volts at 100 knots/volt to 2.5 volts at 200 knots/volt.

The basic scale changing circuit provides an output of less than unity gain; yet, the output information represents the input information. But, ratios as common as 1:2 for the feedback to input leg are not often encountered in analog computer circuits. Usually, the ratio for the feedback to input leg has some odd ratio that is not easily recognized. For instance, consider a circuit that might be used to convert knots into yards-per-second. Knots can be converted to yards/second by multiplying knots by a constant 0.563.

$$\text{Yards/second} = \text{Knots} \times 0.563$$

The ratio of $R_f/R_s$ in the network box provides the constant, 0.563, for the loop shown in figure 2-15. Whenever possible, the resistance of the feedback leg is kept at a value of 1 megohm; therefore, the input leg must have more resistance

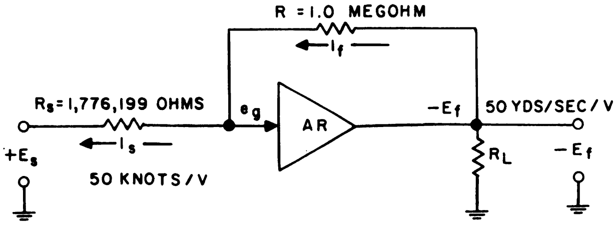

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**Figure 2-15.—A basic circuit for converting knots into yards/seconds.**

to provide the correct ratio. Thus, the ratio of $R_f/R_s$ is

$$\frac{R_f}{R_s} = \frac{1{,}000{,}000}{1{,}776{,}199} \text{ or } 0.563.$$

The scale factors assigned to the input and output of the loop may seem confusing because the input scale factor is 50 knots/volt while the output scale factor is 50 yards/second/volt. However, scale factors are usually expressed in units/volt; therefore, in order for the output to represent the input, the output scale factor already includes the constant, 0.563. This has been done mathematically during the design of the loop.

A comparison of the output and input shows how the output scale factor is expressed as 50 yards/second/volt. When 50 yards/second appears at the output of the loop, −1 volt is dropped across the feedback resistor ($R_f$). The current through $R_f$ is

$$I_f = \frac{E_f}{R_f} = \frac{1}{1{,}000{,}000}; \text{ therefore, } I_f = 0.000001 \text{ amp.}$$

To provide a null at the amplifier input, the input voltage represents some value of knots that is equivalent to 50 yards/second. Mathematically, 50 yards/second can be converted into knots by dividing by the constant, 0.563. This division produces 88.81 knots. Electrically, the constant is provided by the ratio of the network box. As the input scale factor is expressed in knots/volt because of the ratio of $R_f/R_s$, the voltage felt across the input resistor ($R_s$) is larger than the feedback voltage. Thus,

$$E_s = I_s \times R_s$$

$$E_s = 0.000001 \times 1{,}776{,}199$$

$$E_s = 1.776199 \text{ volts.}$$

Therefore, to provide a −1 volt output from the loop, the input voltage must be 1.776 volts. Since the scale factor of the input voltage is 50 knots/volt, this voltage represents 88.81 knots (1.776 × 50 knots/volt = 88.81). Some input and output voltages and what each represents are tabulated in table 2-3.

Recall that the ratio of $R_f/R_s$ controls the overall gain of the loop. The resistance value of the input resistor, for the loops discussed, was equal to or larger than the feedback resistor; therefore, the loop gain was equal to or less than

**Table 2-3.—Input/Output Voltage Converted From Knots to Yards Per Second**

| Input Voltage | Represents Knots | Output Voltage | Represents Yards/second |
|---|---|---|---|
| 1V | 50 | 0.563V | 28.15 |
| 2V | 100 | 1.126V | 56.30 |
| 3V | 150 | 1.689V | 84.45 |
| 4V | 200 | 2.252V | 112.60 |
| 5V | 250 | 2.815V | 140.75 |
| 6V | 300 | 3.378V | 168.90 |
| 7V | 350 | 3.941V | 197.05 |
| 8V | 400 | 4.504V | 225.20 |
| 9V | 450 | 5.067V | 253.35 |
| 10V | 500 | 5.630V | 281.50 |

167.748

unity. If the resistance of the input resistor is less than that of the feedback resistor, the overall gain of the loop is increased. For instance, consider the circuit in figure 2-16 which might be used to convert yards into feet.

Since there are 3 feet in each yard, the ratio of $R_f/R_s$ is selected as 3:1. The scale factor of the output voltage already includes the constant, in this case, 3. With a 1-volt input to the loop, the output is as follows:

$$-E_f = E_s\ (R_f/R_s)$$

$$-E_f = 1(.9/.3)$$

$$E_f = -3 \text{ volts}$$

Therefore, this loop has an overall gain of 3:1; that is, a 1-volt input produces 3 volts at the output. If 1 volt at the output represents 270 feet, then, 3 volts × 270 feet = 810 feet, which is the same as 270 yards.

Again, a comparison of output to input shows how the output scale factor is expressed in feet/volt while the input scale factor is in yards/volt. The ratio of $R_f/R_s$ is such that only .333 volts is required at the input of the loop to produce a −1 volt output. Several input and output voltages and the distance each represents are tabulated in table 2-4.

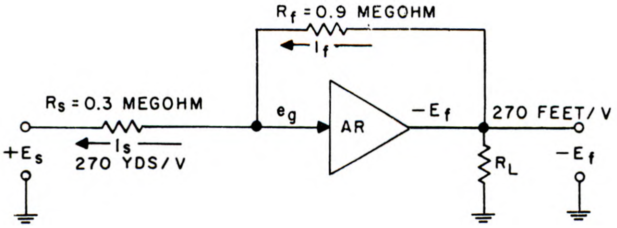

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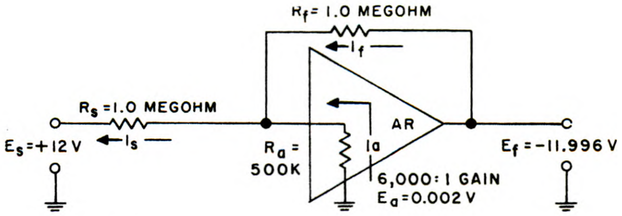
Figure 2-16.—A basic circuit for converting yards into feet.

## GAIN COMPENSATING RESISTOR

During the discussion of the various loops, the slight voltage drop across the input impedance of the amplifier, as mentioned earlier, has been neglected. A close look at the overall circuit shows that the output is not quite equal to the input if this is neglected. The loop diagrammed in figure 2-17 uses a low gain amplifier to show the loss.



$I_s = I_a + I_f$

$I_s$ = E/R ; 12/1,000,000 = 0.000012 amp OR 12 μa.

$I_a$ = E/R ; .002/500,000 = 0.000000004 amp OR 4000 μμa.

$I_f = I_s - I_a$; $I_f$ = 12 μa − 4,000 μμa = 11.996 μa.

$E_f = I_f \times R_f$ ; $E_f$ = 1.0 MEGOHM X 11.996 μa = 11.996 VOLTS. THUS, THE OUTPUT IS 0.004 VOLTS LESS THAN THE INPUT.

167.76

Figure 2-17.—Loss of output voltage due to input impedance of amplifier.

Table 2-4.—Input/Output Voltage Converted From Yards to Feet

| Input Voltage | Represents | Output Voltage | Represents |
|---|---|---|---|
| 0.333V | 90 yards or 270 feet | 1V | 270 feet or 90 yards |
| 0.667V | 180 yards or 540 feet | 2V | 540 feet or 180 yards |
| 1.000V | 270 yards or 810 feet | 3V | 810 feet or 270 yards |
| 1.333V | 360 yards or 1,080 feet | 4V | 1,080 feet or 360 yards |

167.749

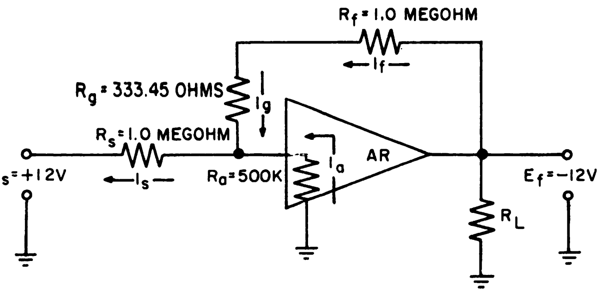


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**Figure 2-18.—Gain compensating resistor used to increase output voltage.**

To correct this slight loss, a gain compensating resistor ($R_g$) is placed in series with the feedback resistor (fig. 2-18). The value of the resistor is chosen so that with a +12 volt input, the output is exactly −12 volts.

In addition to compensating for the slight drop across the amplifier, the gain compensating resistor also reduces the feedback current by the exact amount of $I_a$ so that the original assumption where $I_a$ was assumed to be zero is now compensated for because $I_s = (I_f - I_a) + I_a$. Therefore, $I_s = I_f$ is a true statement.

The size of the gain compensating resistor (fig. 2-18) can be computed using the current through the feedback leg and the voltage dropped across $R_f$. The voltage drop across $R_g$ is determined as follows (using values determined in figure 2-17):

$$E_g = E_s - E_f$$

Thus, $E_g = 12 - 11.996$, or 0.004 volts.

The current through $R_g$ is the same as that through $R_f$, thus,

$$I_g = I_s - I_a;$$

$$I_g = 1^2\ \mu a - 4000\ \mu\mu a, \text{ or } 11.996\ \mu a.$$

Substituting these values into the formula,

$$R_g = \frac{E_g}{I_g},$$

the value of the gain compensating resistor is determined. Thus,

$$R_g = \frac{0.004}{0.000011996} \text{ or } 333.45 \text{ ohms.}$$

The feedback resistor and gain compensating resistor are in series; therefore, the total resistance of the feedback leg is

$$R_{tf} = R_f + R_g;$$

$$R_{tf} = 1{,}000{,}000 + 333.45 = 1{,}000{,}333.45 \text{ ohms.}$$

With more resistance in the feedback leg than in the input leg, the amplifier produces −12 volts, thus compensating for the loss of voltage because of the input impedance of the amplifier. Thus, the voltage out is

$$E_{out} = I_f \times R_{tf};$$

$$E_{out} = .000011996 \times 1{,}000{,}333.45, \text{ or } -12 \text{ volts.}$$

Normally, the schematic of a network box does not show the gain compensating resistor, which does nothing but compensate for the loading effect of the amplifier.

From this discussion you can see that a particular network box is designed for an amplifier having a specific gain. The feedback amplifier has been standardized to a great extent and is interchangeable with another having the same drawing number.

## SUMMATION OPERATIONS

Summation operations (addition and subtraction) are fundamentally important. Take the solution of the fire control problem. Here it is necessary to perform summation many times. In analog computers, the computer variables are converted into electrical signals, then combined in a loop called a summing computing loop. A typical summing computing loop includes either a summing amplifier or a servomechanism, depending on whether an electrical or mechanical output is desired. If an electrical output is needed, an amplifier is used. If the output is mechanical, then a servomechanism is used. In either case, the summation operation is performed by a network box.

### Basic Summing Computing Loop

The loops discussed earlier, which used network boxes, did not add voltages. For a loop to perform summation, two or more input voltages are required. Such a loop is shown in figure 2-19. The loop determines the algebraic sum of three input voltages. To perform summation, a four-legged network box is used, three legs for the input voltage and the fourth leg for the feedback voltage. The feedback leg is sometimes referred to as the great equalizer because it carries the current that balances or nulls out the currents in the other legs.

The three voltages to be added have the same scale factor (1,000 yards/volt). The resistance ratios ($R_f/R_1$, $R_f/R_2$, $R_f/R_3$) are chosen to provide summation of the voltages without a scale change; therefore, the output voltage should be 11 volts with a scale factor of 1,000 yards/volt, or a total of 11,000 yards.

$$I_f = I_1 + I_2 + I_3$$

Substituting Ohm's Law:

$$E_f/R_f = E_1/R_1 + E_2/R_2 + E_2/R_2$$

Multiplying both sides by $R_f$:

$$E_f = E_1 (R_f/R_1) - E_2 (R_f/R_2) - E_3 (R_f/R_3)$$

Substituting known values:

$$-E_f = 5(1/1) + 2(1/1) + 4(1/1)$$

$$-E_f = 5 + 2 + 4$$

$$E_f = -11 \text{ volts.}$$

As the ratio of the feedback leg to each of the inputs is 1:1, then the scale factor of the output voltage is the same as the inputs, or 1,000 yards/volt. Therefore, 11 volts at 1,000 yards/volt represent a total of 11,000 yards. Thus, the summing computing loop uses a multiple input network box to produce an output, which is the sum of its three inputs. The sign of the output voltage is negative because of the odd number of stages in the amplifier. However, if a negative voltage cannot be used at this stage of computation, a sign reversing loop could be used to reverse the polarity of the voltage.

Although addition has been explained as a summation of voltages, the real job of the summing computing loop is to add physical units, such as yards and knots. Therefore, knowledge in equals knowledge out. Thus, each computing loop has scale factors assigned.

## Summation Of Voltages With Dissimilar Scale Factors

In an analog computer, it is often necessary to add quantities that have different values of units/volt (scale factors). To add these correctly, all the inputs must be converted to a common scale, that is, the same unit/volt. The design engineer selects the suitable ratios for the network box so that each input is converted to a common scale. However, the ratios selected must be such that the output cannot exceed the maximum rated output of the feedback amplifier or the computer reference voltage applied to a potentiometer.

As shown in figure 2-20, three voltages, two positive and one negative, each with a different

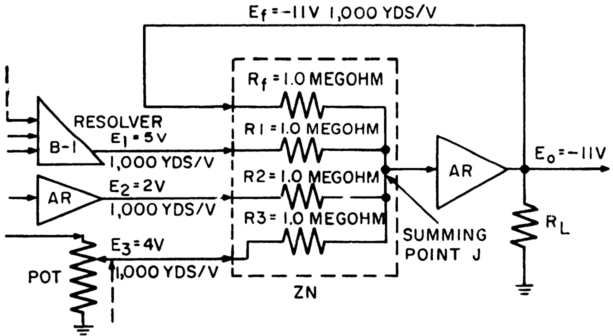

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Figure 2-19.—Basic summing computing loop.

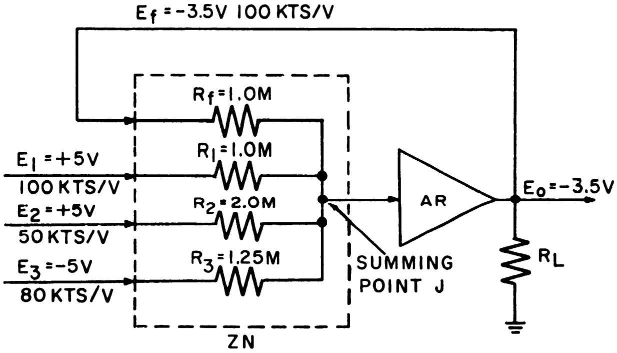

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Figure 2-20.—Summation of voltages with dissimilar scale factors.

value of knots/volt are to be added algebraically by the summing computing loop. The negative input voltage does not present a problem as the current through $R_3$ causes a positive potential at summing point J, which, in effect, reduces the current through the feedback leg. According to Kirchhoff's Law of electrical current, the algebraic sum of the current entering a junction must be equal to the sum of the current leaving the junction. Therefore, the following equation can be written:

$$I_f + I_3 = I_1 + I_2.$$

The above equation can be rewritten as follows to compute the output voltage:

$$I_f = I_1 + I_2 - I_3$$

$$E_f/R_f = E_1/R_1 + E_2/R_2 - E_3/R_3$$

$$E_f = E_1\ (R_f/R_1) + E_2\ (R_f/R_2) - E_3\ (R_f/R_3)$$

$$-E_f = 5(1/1) + 5(1/2) - 5(1/1.25)$$

$$-E_f = 5 + 2.5 - 4$$

$$E_f = -3.5 \text{ volts.}$$

As $R_f$ and $R_1$ have a 1:1 ratio, this sets the common scale factor for the output voltage. Thus,

Common output scale factor =

$E_1$ scale factor $(R_1/R_f)$

Output scale factor =

100 knots/volt (1/1), or 100 knots/volt.

The resistance value of the other two input legs is selected so as to convert the knots/volt ratio to the common scale of 100 knots/volt. Thus, the output scale factors for the other two legs are as follows:

Output scale factor = $E_2$ scale factor $(R_2/R_f)$

Output scale factor = 50 knots/volt (2/1), or 100 knots/volt

Output scale factor = $E_3$ scale factor $(R_3/R_f)$

Output scale factor = 80 knots/volt (1.25/1), or 100 knots/volt.

Therefore, the output factor is common for each of the three input voltages. Thus, the summing computing loop has algebraically added the three voltages with different scale factors to produce an output of 3.5 volts, which represents 350 knots.

The summing computing loop just described is not suited for practical use, but it is sufficient for explaining the summation of positive and negative input voltages and the principles of scale changing. Let's examine the reason for its not being practical.

When a network box is designed for use in a summing computing loop, the design engineer must take into consideration the maximum level of the input voltages as well as the maximum output voltage. The ratio of the feedback leg to each input leg must be such that the amplifier does not saturate. The magnitude of the output voltage, along with the scale factor assigned, must be suitable for the next step of computation.

## MULTIPLICATION AND DIVISION OPERATIONS

Multiplication and division operations in an analog computer are as important as summation operations. Multiplication may be performed electrically by amplifiers, and electromechanically by potentiometers. Multiplication and division in amplifiers was discussed previously and will not be covered here.

In an analog computer, the computer variables to be multiplied may be either voltages or motions (shaft rotations or positions). Therefore, multiplication of two variables may be performed by one of the following methods: volts × motion, motion × motion, and volts × volts. Multiplication by each of these methods is discussed, and where the same elements can be used for division, this operation is also covered.

### Multiplication Of Two Variables With A Potentiometer

In the discussion of potentiometers, the pot was used to convert a mechanical computer variable into a corresponding electrical value. This is referred to as mechanical-to-electrical conversion. Actually, the pot multiplied a mechanical shaft position by a constant voltage; or, in other words, a variable was multiplied by a constant.

The pot shown in figure 2-21 multiplies two computer variables, one electrical and the other mechanical; this demonstrates volts times motion multiplication. The potentiometer is energized by a voltage that can vary from − 10 to + 10 volts. This voltage represents a rate that is expressed in knots/volt. The mechanical input represents time in seconds, and it can be varied from 0 seconds to 50 seconds at 5 seconds per turn of the 10-turn pot. The output represents a distance and is expressed in yards/volt. Thus, the potentiometer performs any multiplication problem within limitations, involving rate × time = distance.

Previously, knots were converted to yards/second by the use of a constant (0.563). The electrical scale factor (2.815 yards/volt) includes the conversion of knots to yards/second; therefore, the constant 0.563 is there but not seen. However, if a problem is computed mathematically, the constant must be used.

The output scale factor can be determined by using the maximum input voltage and the two input scale factors. Thus,

maximum input of knots is

$$100 \text{ Kts/V} \times 10 \text{ volts} = 1{,}000 \text{ knots;}$$

maximum yards/second is

$$1{,}000 \text{ knots} \times 0.563 = 563 \text{ Yds/Sec;}$$

maximum yards/output is

$$563 \text{ Yds/Sec} \times 50 \text{ seconds} = 28{,}150 \text{ yards;}$$

output in yards/volt is

$$28{,}150 \text{ yards}/10 \text{ volts} = 2{,}815 \text{ Yds/V.}$$

If + 6 volts were the input voltage and the slider were positioned to represent 20 seconds, the output voltage would be 2.4 volts. This voltage represents 6,756 yards. Mathematically, this can be proven as follows:

$$6 \text{ volts at } 100 \text{ Kts/V} = 600 \text{ knots}$$

$$600 \text{ knots} \times 0.563 = 337.8 \text{ Yds/Sec}$$

$$337.8 \text{ Yds/Sec} \times 20 \text{ Sec} = 6{,}756 \text{ yards}$$

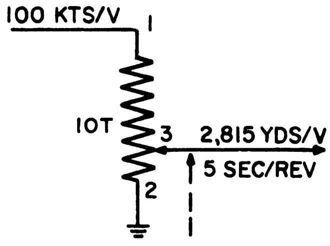

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**Figure 2-21.—Potentiometer multiplication of two variables.**

Previously, in the study of pots, you saw that for one position of the slider a certain output voltage was obtained because the input voltage was constant. However, when the input voltage is variable, many different output voltages can be obtained for a given position of the slider. For example, several possible output voltages are listed below for the 20-second position of the slider, which is 0.4 of the total travel.

| Input | Output |
|---|---|
| 1,000 knots = + 10 volts | 10V × .4 = 4V or 11,260 yds |
| 800 knots = + 8 volts | 8V × .4 = 3.2V or 9,008 yds |
| 600 knots = + 6 volts | 6V × .4 = 2.4V or 6,756 yds |
| 400 knots = + 4 volts | 4V × .4 = 1.6V or 4,504 yds |
| 200 knots = + 2 volts | 2V × .4 = 0.8V or 2,252 yds |
| 100 knots = + 1 volts | 1V × .4 = 0.4V or 1,126 yds |
| 0 knots = 0 volts | 0V × .4 = 0.0V or zero yds |
| − 300 knots = − 3 volts | − 3V × .4 = − 1.2V or 3,378 yds |
| − 500 knots = − 5 volts | − 5V × .4 = 2.0V or 5,630 yds |
| − 700 knots = − 7 volts | − 7V × .4 = − 2.8V or 7,882 yds |
| − 900 knots = − 9 volts | − 9V × .4 = − 3.6V or 10,134 yds |

### Double-Ended Potentiometer As A Multiplier

Previously, a double-ended potentiometer was used to represent electrically a variable that could be either plus or minus with respect to a zero reference. Each end of the pot had an applied voltage—one end with a plus voltage, the other with a negative voltage. However, some analog computers also use a double-ended pot to solve multiplication problems similar to the one just studied.

Figure 2-22 shows a double-ended pot that can do the same multiplication problem just discussed. Each end of the pot has an applied voltage that represents time. Plus and minus voltages are used because the rate can be either plus or minus with respect to a zero reference. Therefore, a positive rate produces a plus voltage and a negative rate produces a minus voltage. The mechanical input represents the rate and is expressed in yards/second. The conversion from knots to yards/second has already been done. The zero position of the slider is at the center of the potentiometer, as is the case for all double-ended potentiometers. Thus, from the center of the potentiometer to either end represents 563 yards/second, or a total of 1,126 yards/second. A 10-turn potentiometer is used, and, therefore, the mechanical scale factor is 112.6 Yds/Sec/Rev.

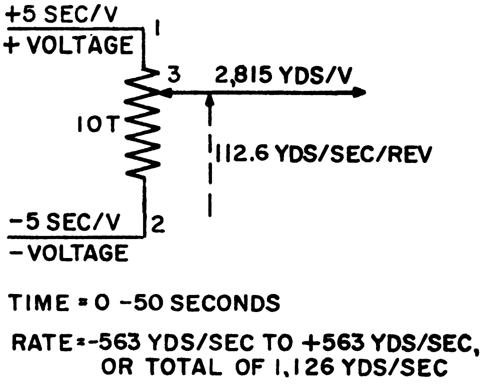

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Figure 2-22.—Double-ended potentiometer multiplication of two variables.

The slider movement from the center to either end of the potentiometer will represent 1,000 knots (563 Yds/Sec/.563).

If the same multiplication problem, +600 knots × 20 seconds = 6,756 yards, were presented to the potentiometers, the following conditions would exist:

±4 volts would energize the potentiometer, thus representing 20 seconds (4 volts × 5 Sec/V = 20 seconds).

To represent +600 knots, the slider is rotated 3 revolutions so that the slider moves upward from the center a total of 337.8 Yds/Sec (3 Rev × 112.6 Yds/Sec/Rev = 337.8 Yds/Sec, or 600 knots).

The output voltage will be +2.4 volts (+4 volts × 2(3/10) = +2.4 volts).

+2.4 volts, whose scale factor is 2,815 Yds/V, therefore, represents 6,756 yards (2,815 Yds/V × 2.4 volts = 6,756 yards).

### Cascading Potentiometers For Multiplication

So far, in our discussion of linear potentiometers, we have assumed that the output is connected to a high impedance, which does not draw any appreciable amount of current from the potentiometer. Therefore, the output is directly proportional to the angle of rotation of the potentiometer shaft multiplied by the input voltage or $E_o = E_{in} \times \theta$. This equation may be rewritten as $E_o = E_{in} (R/R_t)$ if the potentiometer is labeled as shown in figure 2-23. Thus, when the input is 10 volts and the slider is positioned at its center of travel, the open-circuit voltage at the slider is 5 volts if measured with a vacuum tube voltmeter. However, if an ac voltmeter with an impedance of 1,000 ohms/volt is used to measure the output voltage, the meter draws current and the output voltage is reduced to 4.444 volts. This type of ac voltmeter should not be used to measure the output voltage from a computing potentiometer. The output voltage

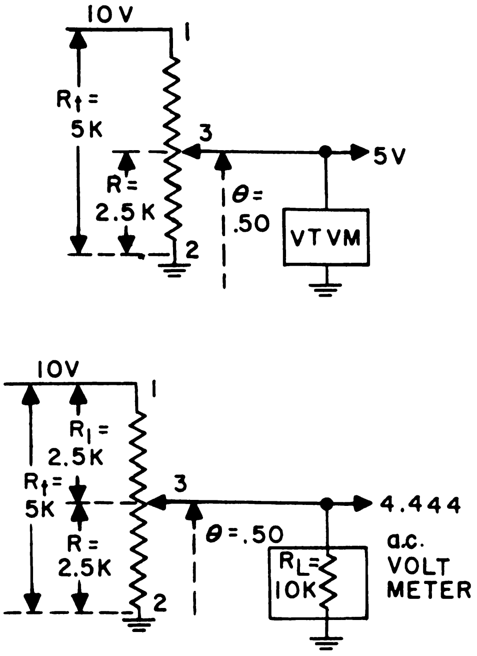

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Figure 2-23.—Loading effect of an ac voltmeter.

is determined by first computing the effective resistance of the circuit using the formula for effective resistance. Be careful, make certain you understand which resistance of the parallel branch is acting as an effective total resistance. It may be to your advantage to review the method of calculating effective resistance.

To obtain the electrical product of two mechanical variable, two pots may be used. This is referred to as motion × motion multiplication. However, if the pots are connected as shown in figure 2-24, view A, the second pot draws current, thus loading the first pot. As a result, the output voltage of the first pot is not proportional to shaft rotation but is less than that value by an amount that depends on the current drain as well as the position of the slider and its total resistance. Hence, the output of the second pot would be in error even though the output is connected to a high impedance load, because the potentiometers are connected so that a series parallel circuit is formed, as shown in part B of the figure.

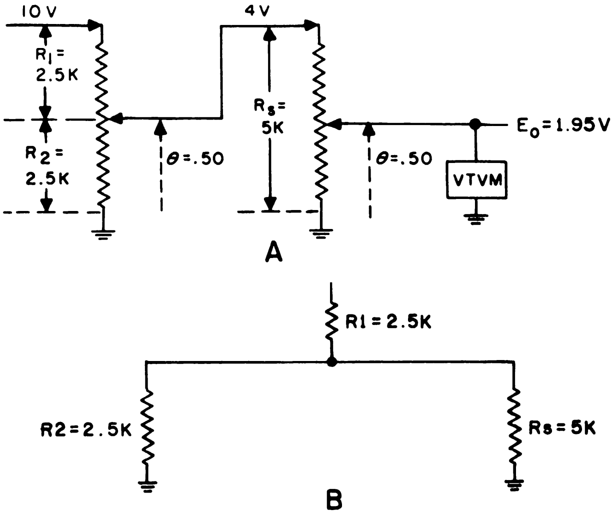

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Figure 2-24.—A. Loss of voltage due to loading a potentiometer, B. Series parallel circuit formed.

The formula for computing the total effective resistance of the circuit can be used.

$$\text{Total } R_{eff} = R_1 + \text{Effective R of } R_s \text{ and } R_2$$

$$\text{Total } R_{eff} = R_1 + \frac{R_s + R_s}{R_s + R_2}$$

$$= 2.5\text{K} + \frac{12.5\text{K}}{7.5\text{K}}$$

$$= 2.5\text{K} + 1.6\text{K}$$

$$= 4.1\text{K ohms}$$

This effective resistance of the circuit is then used to determine the voltage applied to the second potentiometer, which can be found by using the ratio

$$\frac{\text{Input voltage}}{\text{Total effective resistance}} = \frac{\text{X (voltage applied to second pot)}}{\text{Effective resistance of } R_s + R_2}$$

$$\frac{10 \text{ volts}}{4.1\text{K ohms}} = \frac{\text{X}}{1.6\text{K ohms}}$$

$$(\text{X})\ (4.1\text{K}) = 16\text{K}$$

$$\text{X} = 3.9 \text{ volts.}$$

This 3.9 volts is applied to $R_s$; the slider of $R_s$ is at its center of travel (50%). The voltage out ($E_o$) from $R_s$ equals

$$\begin{aligned} E_o &= E_{in} \times \theta \\ &= 3.9 \times 0.5 \\ &= 1.95 \text{ volts.} \end{aligned}$$

To eliminate the error in the output due to loading, the two potentiometers are isolated from each other with a network box and a feedback (isolation) amplifier, shown in figure 2-25. With the loading effect eliminated, the output is an accurate 2.5 volts. This is because $R_2$ is no longer in parallel with $R_s$, but it is in parallel with the input to the network box.

If the potentiometers are ganged together, as shown in figure 2-26, and the mechanical input is designated as the X input, then the output is equal to $E_{in}$ $X^3$. Thus, potentiometers may be used to raise the power of an input (X). If a fourth potentiometer is used, the variable X is raised to the fourth power, and so on, by adding pots.

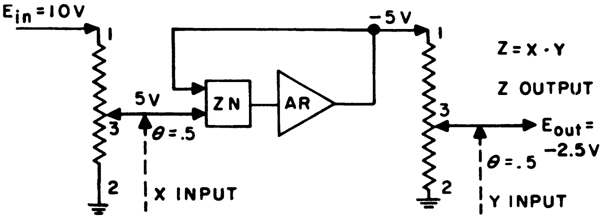

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**Figure 2-25.—Elimination of loading effect for accurate multiplication.**

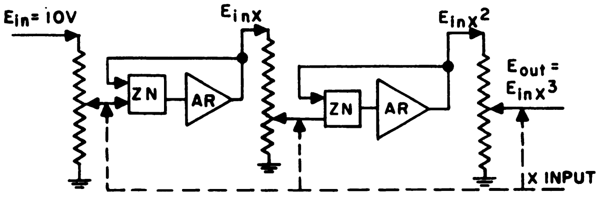

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**Figure 2-26.—Powers by successive multiplication.**

## Division With Potentiometers

Potentiometers can be used to perform division as well as multiplication. When two potentiometers are used for multiplication, the output is taken from the slider of the second potentiometer. To perform division, the output from the slider is fed back as a nulling voltage to the network box. The equation solved is $Z = X/Y$.

There are two facts known about the elements in a divider loop; a potentiometer is a multiplier, and a two-legged network box has equal knowledge (not necessarily equal voltage) on each leg. In addition to these two known facts for the loop to perform division, the input-output ratio of the amplifier must be variable.

Looking at figure 2-27, view A, there are two variables in the circuit. The first is the input voltage into the network box (X input), the second is the amount of voltage fed back to the network box (determined by the Y input). The output of the loop is unknown and is called (Z). Potentiometer $R_1$ is supplied with a voltage, in

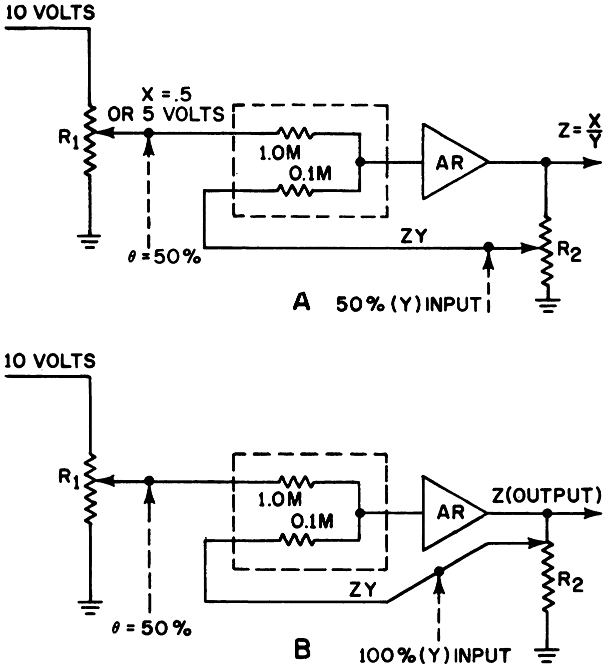

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**Figure 2-27.—A. Divider loop using potentiometers; B. Divider loop operation.**

this problem, 10 volts. The slider is moved through an angle X = .5 or 50%, and the output from the slider is 5 volts. $R_2$ is supplied with the amplifier output (Z) and the slider is moved through an analog, which is the Y input. Potentiometer $R_2$ actually multiplies the input voltage (Z) by the position of its slider (Y), and the output voltage (ZY) is the other input to the network box. As the output of the network box is theoretically zero, then

$$0 = X - ZY$$

$$\text{or} \quad ZY = X$$

$$\text{then} \quad Z = \frac{X}{Y}.$$

Taking into consideration the ratio of the network box resistances, the output is

$$Z = \left(\frac{R_f}{R_s}\right) \frac{X \text{ voltage}}{Y \text{ voltage}}.$$

Because of the ratio ($R_f/R_s$) of the network box and the X input, only 0.5 volt is required to null the 5-volt input to the network box. This can be shown by moving the slider of the potentiometer $R_2$ to 100% of its travel; then, the output of the amplifier is fed directly to the feedback leg of the network box, which is shown in figure 2-27. The problem then becomes

$$Z = \left(\frac{R_f}{R_s}\right) \frac{X \text{ voltage}}{Y \text{ voltage}}.$$

$$= \frac{.1}{1} \times \frac{5}{1}$$

$$= 0.5 \text{ volt.}$$

As long as the input remains 5 volts, the feedback voltage will be 0.5 volt; but the output of the amplifier will vary as the Y input is changed, picking off a portion of the amplifier output.

Therefore, the gain of the amplifier is variable depending on the position of the slider of $R_2$. However, if the 5-volt input is changed, the amount of feedback voltage required to null this change will vary accordingly. For example, if the X input voltage is changed to 8 volts (representing X = .8), the amount of feedback required to null this voltage will be .8 volt.

$$E_f = E_s \frac{R_f}{R_s}$$

$$= 8 \frac{.1}{1}$$

$$= .8$$

Taking the reciprocal of a quantity (fig. 2-28) is also a division process. In a reciprocal circuit, the input to the network box is a constant voltage (computer reference), and the slider of the pot is moved by the mechanical input Y. The voltage output of the amplifier is the electrical reciprocal of the mechanical input, providing the slider is positioned at the top of the pot for maximum input and near ground potential for minimum input.

## SERVO MULTIPLIER

The servo multiplier is used to multiply two voltages together with the output as a voltage. The principle of operation is to first convert one of the voltages to a proportional mechanical displacement or rotation by using a servo. This mechanical quantity moves the slider of a ganged potentiometer to perform the final

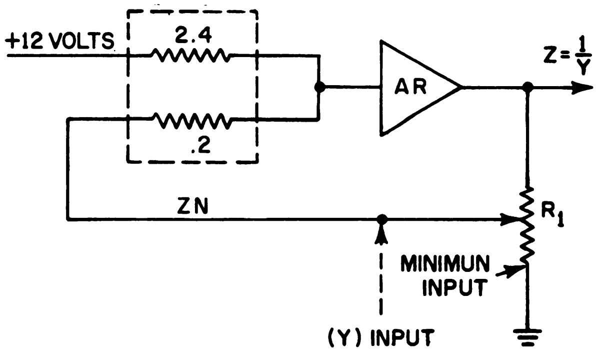

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Figure 2-28.—Basic reciprocal loop using a linear potentiometer.

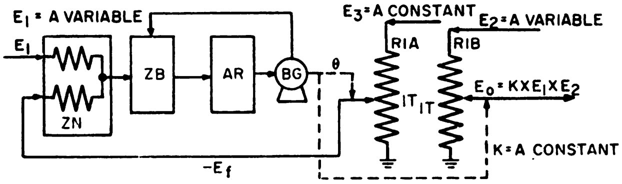

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Figure 2-29.—Volts × volts multiplication with a servo multiplier.

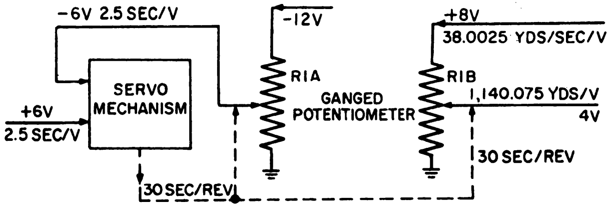

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**Figure 2-30.—Servo multiplier with assigned scale factors.**

multiplication. A servo multiplier is shown in figure 2-29.

The two voltages to be multiplied are designated $E_1$ and $E_2$. Each of these voltages represents a computer variable. Through servo action, the servomotor positions the slider of potentiometer R1A so that the feedback voltage to the network box is always proportional to the input voltage ($E_1$). Bear in mind that the feedback voltage ($E_f$) can represent several input voltages to the network box. Because potentiometer R1A is linear, the output angle $\theta$ is proportional to the input voltage ($E_1$).

Now, let us assign values to voltages $E_1$ and $E_3$. Look at figure 2-29. If $E_3$ is a constant $-12$ volts and $E_1$ is $+6$ volts, the servo will drive until the slider of potentiometer R1A provides $-6$ volts of feedback to the network box. At this time, the servomechanism stops driving and the slider of potentiometer R1A is at 50 percent of a full rotation. Since pots R1A and R1B are ganged together, the slider of R1B is also at 50 percent of a full rotation. Potentiometer R1A provides the feedback voltage to position its slider correctly, and the multiplication will be performed by the potentiometer R1B.

If a value of 8 volts is assigned as the input voltage to potentiometer R1B, the output voltage of the servo multiplier can be determined. Two values concerning the potentiometer are known: first, the slider is positioned at 50 percent of full rotation, and secondly, the input voltage is 8 volts, thus, the equation, $E_0 = E_2 \times$ percent of rotation, can be used to find the output voltage. For this example $E_0$ is 4 volts.

The output voltage can be computed mathematically by using the formula assigned to the output of potentiometer R1B. The formula is

$$E_0 = K \times E_1 \times E_2.$$

The constant K is always the reciprocal of the $E_3$ voltage applied to the feedback or nulling potentiometer (R1A). The constant for this example is 1/12. Therefore, $E_0 = 1/12 \times 6 \times 8$, or 4 volts.

By assigning scale factors to the servo multiplier (fig. 2-30), any rate times time problem can be solved. The scale factors assigned below are for a target capable of traveling at a maximum speed of 810 knots. The computer reference voltage is 12 volts, and the maximum limit of time is 30 seconds. The problem is to convert a 6-volt input, with a scale factor of 2.5 seconds/volt, to a mechanical position and multiply this position by a rate expressed in yards/second/volt. The rate, 540 Kts is represented by the 8-volt input to potentiometer R1B and has a scale factor of 38.0025 yards/second/volt. Therefore, the output voltage represents yards (yards/second × seconds = yards).

The servomechanism positions itself so that potentiometer R1A provides $-6$ volts feedback to the network box to null the input signal of $+6$ volts. This position represents 15 seconds, and potentiometers R1A and R1B are positioned at 50 percent of a full rotation (6V at 2.5 sec/V = 15 sec.).

Potentiometer R1B will perform the multiplication of 15 seconds times 8 volts at 38.0025 yards/sec/volt. The 8 volts times 38.0025 yards/sec/volt will yield the yards/sec (8 × 38.0025 = 304.02). Thus multiplying yards/second × seconds = yards (304.02 × 15 = 4,560.3). The results can be checked by dividing the yardage by the electrical scale factor of the output voltage. Thus,

$$\frac{4{,}560.3 \text{ yards}}{1{,}140.075 \text{ Yds/V}} = 4 \text{ volts.}$$

## TRIGONOMETRIC FUNCTIONS

In electrical analog computers, ac resolvers are used primarily for the solution of right triangles and coordinate rotation. In the solution of a particular problem in a computer, the resolver must be used in conjunction with a network box and summing amplifier. In many cases, the output of a resolver will be the input to other resolvers, until as many as six or seven are connected into a resolver chain. Resolvers are low impedance elements, therefore, to compute accurately, they must be isolated from the preceding element to prevent loading. Isolation is provided by a network box and summing amplifier. The amplifier is sometimes called an isolation or booster amplifier. It has a low output impedance and can correct any undesirable phase shift developed in the resolver. Thus, in actual application, resolvers are connected in what may be referred to as basic resolver loops. *NEETS MODULE 15* contains information on basic resolver operation.

### Basic Resolver Operation

Figure 2-31 shows a circuit diagram of a basic resolver loop. The input voltages are designated as $E_a$ and $E_b$. The voltages are in phase or 180° out of phase with the computer reference voltage. The input voltages are always impressed on the stator windings of a resolver through a network box and isolation amplifier. Signal flow in the stator circuit is somewhat different than that of a sign reversing or summing computing loop. In those loops, the amplifier output is fed directly back to the network box as the feedback voltage. However, in a resolver loop, the output of the amplifier excites the stator winding of the resolver, which induces a voltage in an additional winding called the feedback winding. The voltage induced in the feedback winding is fed back to the network box as the feedback voltage, which must be out of phase with the input voltage to the network box.

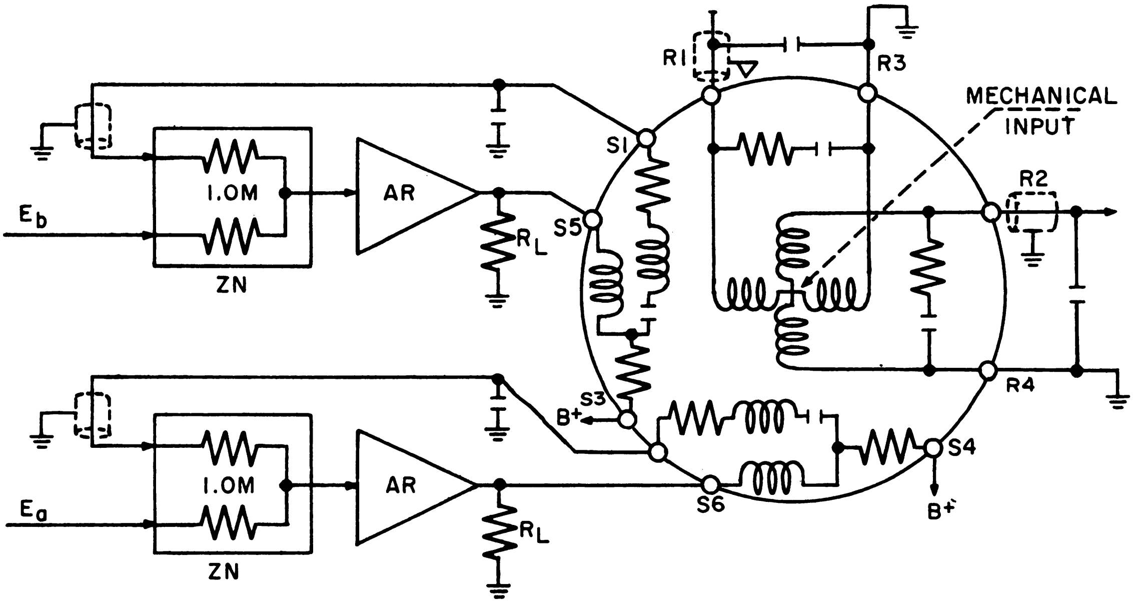

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Figure 2-31.—Basic resolver loop.

The magnitude of the amplifier output is less than the input voltage to the network box, and a slight phase shift is designed into the loop to compensate for the phase shift developed in the resolver. There is a slight step-up of voltage between stator and rotor so that unity gain is achieved between the input of the loop (at the network box) and the output. In addition, to help achieve the unity gain desired and resolver interchangeability, the feedback and output leads are trimmed with a capacitor to provide a constant value of capacitance (up to 2,000 μμfd in some computers). These leads are coaxial cables and naturally have a certain capacitance per foot; therefore, trimming is necessary so that the various lengths of cables are made uniform in capacitance. The shields of the coaxial leads are grounded.

The amplifier output is also connected to a load resistor for proper operation of the amplifier. The load resistor may be mounted within the network box or mounted externally.

When the voltage at Eb is zero and the Ea voltage is of some nominal magnitude, the voltage induced in the R1-R3 winding will be equal to the Ea voltage and of the same phase, providing the rotor is at its zero position. At this zero position of the rotor, zero volts will be induced in the R2-R4 winding.

Clockwise rotation of the rotor will cause a voltage to be induced in the R2 winding that is out of phase with the Ea voltage. Counterclockwise rotation of the rotor will cause a voltage to be induced in the R2 winding that is in phase with the Ea voltage. When the rotor is at a position so that these conditions are met, the resolver is said to be on electrical zero.

Once the electrical zero position of a resolver has been set, problems involving resolution, composition, and coordinate rotation can be solved by the resolver. To solve problems, the voltages induced in the rotor windings follow an established equation depending on the polarity of the Ea and Eb inputs, the rotor lead selected, and the direction of rotation of the rotor. For example, assume that Ea and Eb are +8 volts, and the rotor is rotated 30° clockwise. The voltages induced in rotor leads R1 and R2 are as follows: (Negative values are determined by phase comparison.)

$$R1 = Ea\cos 30^\circ + Eb\sin 30^\circ$$

$$8(.866) + 8(.5)$$

$$6.928 + 4$$

$$10.928 \text{ volts}$$

$$R2 = Ea\sin 30^\circ + Eb\cos 30^\circ$$

$$-8(.5) + 8(.866)$$

$$-4 + 6.928$$

$$+2.928 \text{ volts}$$

For the same Ea and Eb inputs, rotation of the rotor counterclockwise a total of 30° will cause different voltages to be induced in R1 and R2. The voltages induced are as follows:

$$R1 = Ea\cos 30^\circ - Eb\sin 30^\circ$$

$$8(.866) - 8(.5)$$

$$6.928 - 4$$

$$+2.928 \text{ volts}$$

$$R2 = Ea\sin 30^\circ + Eb\cos 30^\circ$$

$$8(.5) + 8(.866)$$

$$4 + 6.928$$

$$+10.928 \text{ volts}$$

Compare these voltages with those obtained when the rotor was rotated clockwise.

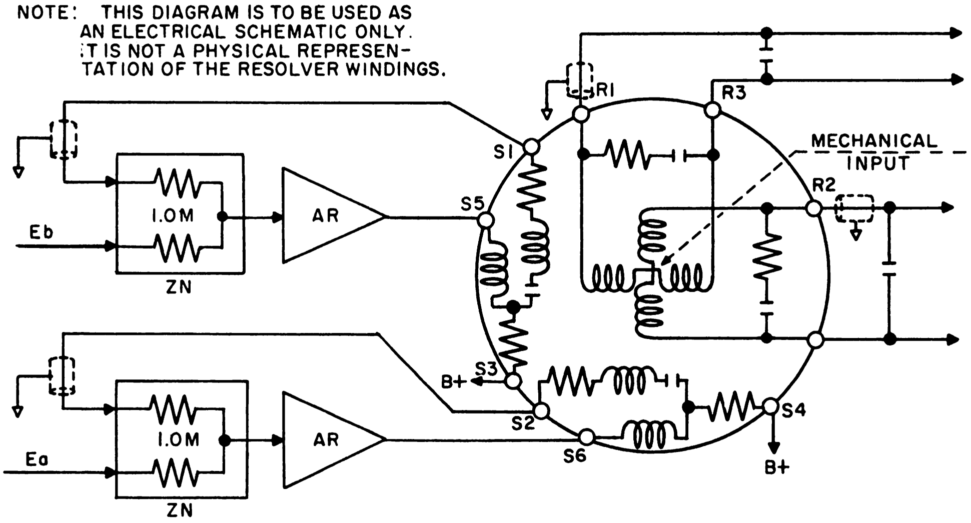
| ROTATION OF ROTOR | R1 OUTPUT | R2 OUTPUT |
|---|---|---|
| CW | +10.928V | + 2.928V |
| CCW | + 2.928V | +10.928V |

From the preceding comparison, it can be seen that the direction of rotation of the rotor has a very important bearing on the output voltages obtained. The preceding problems used a plus value of Ea and Eb. If either or both were negative, the outputs would naturally change.

The table in figure 2-32 shows the various combinations of output voltages available from a resolver under different conditions. The second and third columns indicate the condition of the rotor connections: HIGH meaning the output lead, LOW SIDE meaning the rotor lead is grounded. The next column shows the direction of the rotor from electrical zero. The next four columns show the output function in relation to the polarity of the Ea and Eb inputs.

Refer to the table shown in figure 2-32 and consider the preceding example where the rotor was rotated counterclockwise. Both Ea and Eb were positive and the R1 and R2 windings were the outputs. Under the HIGH column, locate the two lines where R1 is high (lines 1 and 5). The ROTATION column is used next to determine which of the two lines to use. In this case, since the rotor was turned counterclockwise, use line 5. To read the output function from the R1 rotor lead, locate the OUTPUT FUNCTION listed in the +Ea +Eb column. This reads Ea Cos $\theta$ − Eb Sin $\theta$, which is the same output function used to compute the R1 voltage in the preceding example.

The OUTPUT FUNCTION of the R2 winding is read on line 7 under the same output function column. This line reads Ea Sin $\theta$ + Eb Cos $\theta$,


NOTE: THIS DIAGRAM IS TO BE USED AS AN ELECTRICAL SCHEMATIC ONLY. IT IS NOT A PHYSICAL REPRESENTATION OF THE RESOLVER WINDINGS.
Eb
1.0M
ZN
AR
Ea
1.0M
ZN
AR
S1
S5
S3
B+
S2
S6
S4
B+
R1
R3
R2
MECHANICAL INPUT

| | HIGH | LOW SIDE | ROTATION | OUTPUT FUNCTIONS | | | |
|---|---|---|---|---|---|---|---|
| | | | | +Ea +Eb | +Ea −Eb | -Ea -Eb | -Ea + Eb |
| 1 | R1 | R3 | CW | EaCos$\theta$+EbSin$\theta$ | EaCos$\theta$-EbSin$\theta$ | -EaCos$\theta$-EbSin$\theta$ | -EaCos$\theta$+EbSin$\theta$ |
| 2 | R3 | R1 | CW | -EaCos$\theta$-EbSin$\theta$ | -EaCos$\theta$+EbSin$\theta$ | EaCos$\theta$+EbSin$\theta$ | EaCos$\theta$-EbSin$\theta$ |
| 3 | R2 | R4 | CW | -EaSin$\theta$+EbCos$\theta$ | -EaSin$\theta$-EbCos$\theta$ | EaSin$\theta$-EbCos$\theta$ | EaSin$\theta$+EbCos$\theta$ |
| 4 | R4 | R2 | CW | EaSin$\theta$-EbCos$\theta$ | EaSin$\theta$+EbCos$\theta$ | -EaSin$\theta$+EbCos$\theta$ | -EaSin$\theta$-EbCos$\theta$ |
| 5 | R1 | R3 | CCW | EaCos$\theta$-EbSin$\theta$ | EaCos$\theta$+EbSin$\theta$ | -EaCos$\theta$+EbSin$\theta$ | -EaCos$\theta$-EbSin$\theta$ |
| 6 | R3 | R1 | CCW | -EaCos$\theta$+EbSin$\theta$ | -EaCos$\theta$-EbSin$\theta$ | EaCos$\theta$-EbSin$\theta$ | EaCos$\theta$+EbSin$\theta$ |
| 7 | R2 | R4 | CCW | EaSin$\theta$+EbCos$\theta$ | EaSin$\theta$-EbCos$\theta$ | -EaSin$\theta$-EbCos$\theta$ | -EaSin$\theta$+EbCos$\theta$ |
| 8 | R4 | R2 | CCW | -EaSin$\theta$-EbCos$\theta$ | -EaSin$\theta$+EbCos$\theta$ | EaSin$\theta$+EbCos$\theta$ | EaSin$\theta$-EbCos$\theta$ |

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**Figure 2-32.—Standards for resolver Mk 4 Mod 3.**

which is the same output function used in the original example.

When only one stator is energized, the input voltage is applied as the Ea input. Therefore, only the Ea side of the equation is used; the Eb portion is deleted.

## Basic Resolver Loop (Practical Application)

The basic equations for resolvers used in this example (fig. 2-33) are

$$R1 = X \text{ Sin } + Y \text{ Cos}$$

$$R2 = X \text{ Cos } - Y \text{ Sin.}$$

The outputs are not the actual phase of the output voltage but merely indicate that the induced voltages will add or subtract when the rotor is in the first quadrant. To produce the above equations, stator windings S1 and S2 are supplied with a positive voltage (positive with respect to ground at the resolver, not the input to the amplifier), and the resolver rotor is rotated clockwise for an increasing quantity. Notice how the rotor is rotated in relation to the stator windings. This will be helpful when you actually phase out a resolver loop. When a resolver is replaced, the loop must be adjusted to provide unity gain between the input to the loop and the output. Two adjustments are involved—the phase and the gain adjustments.

> The basic objective is to adjust the loop so that the output voltage of the rotor has the same phase and amplitude as the input voltage to the amplifier when the rotor is at its zero position.

At the zero position of the rotor, the winding concerned is parallel to the stator winding that is inducing the voltage in it. In this position, there should be unity gain, or one-to-one transformation, between the input to the amplifier, and the resolver output and a zero phase shift should take place. If unity gain or the desired phase

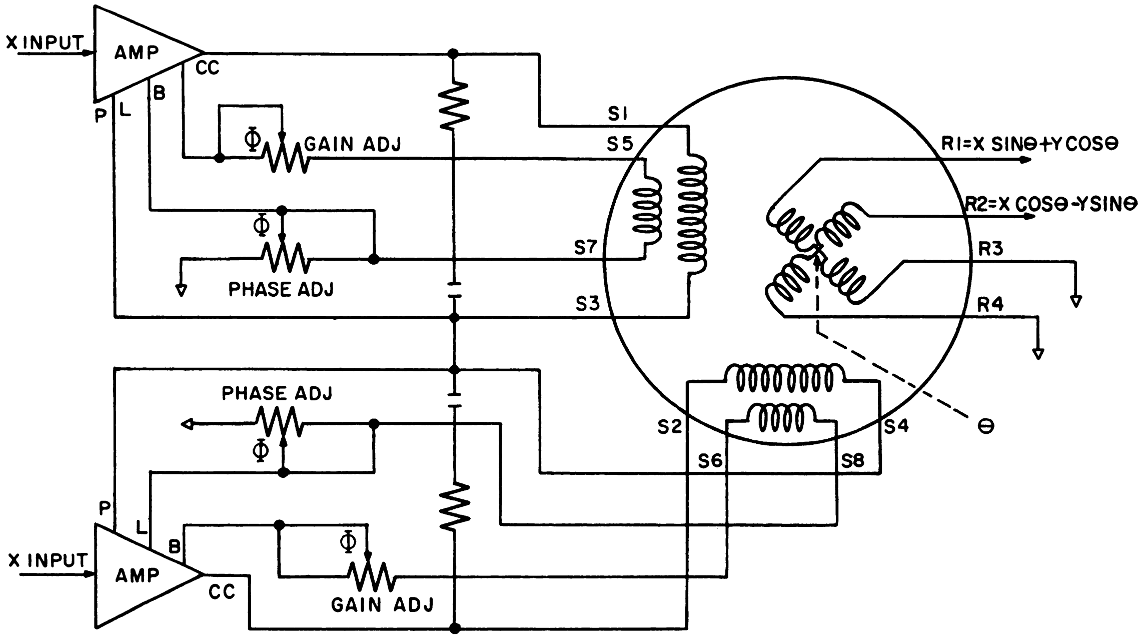

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Figure 2-33.—Basic resolver loop—practical application.

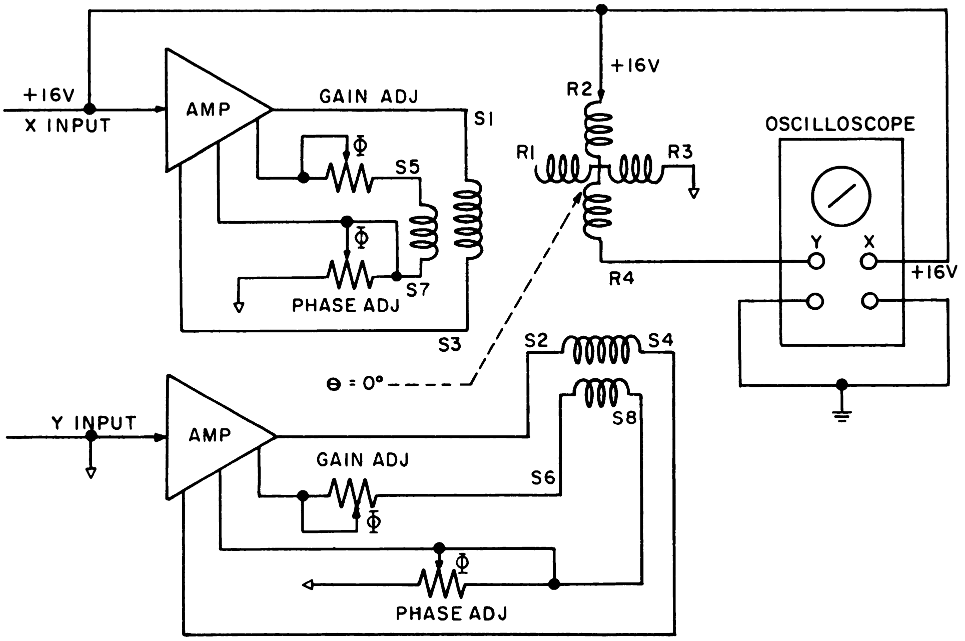

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Figure 2-34.—Oscilloscope connections for adjusting phase and gain of a resolver loop.

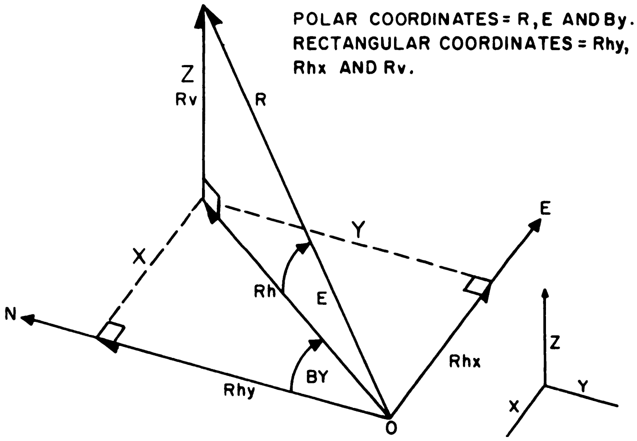
shift is not achieved, then the phase and gain adjustments must be made so that the amplifier output is changed in both phase and magnitude to provide the proper output from the resolver.

Figure 2-34 shows the connections for making the gain and phase adjustments for the X input. The Y input is grounded, and all grounds shown must be common. The Lissajous pattern on the oscilloscope should make a diagonal figure eight, compressed in height as much as possible.

## Resolution

One of the trigonometric functions a resolver is capable of handling is the resolution of a vector. This is the process of taking a vector in its polar form and resolving it into its two rectangular components. To accomplish resolution with a resolver, one electrical input and one mechanical input are required. Two electrical outputs are obtained.

Two resolvers can be used to resolve present target position (a vector in polar form) into three voltages representing target position in Cartesian (rectangular) coordinates. Figure 2-35 shows the geometry of the problem and


POLAR COORDINATES = R, E AND By.
RECTANGULAR COORDINATES = Rhy, Rhx AND Rv.
Z
Rv
R
X
Y
E
N
Rh
E
BY
Rhy
Rhx
O
Z
Y
X

167.102

Figure 2-35.—Defining the position of a point in space by rectangular and polar coordinate systems.

figure 2-36 is a schematic diagram of a typical resolver chain that changes (transforms) polar coordinates into rectangular coordinates.

The electrical input to resolver BR-1 is range R. The rotor is mechanically positioned by target elevation E. The output from rotor lead R4 is target height Rv or the Z axis of a rectangular coordinate system. This is one of the electrical quantities desired. The output obtained from rotor lead R3 is horizontal range Rh. Thus, the rectangular components (Rh and Rv) of the vector represented by R (its magnitude) and E (its direction) have been determined.

Horizontal range Rh (it can be thought of as the length of a new vector lying in the horizontal plane) is the electrical input to resolver BR-2. The rotor is mechanically positioned by true target bearing By (the direction of vector Rh). The output from rotor lead R3 is north-south horizontal range, Rhy or the Y axis of a rectangular coordinate system. The output from rotor lead R4 is eastwest horizontal range Rhx (the X axis). The outputs are the two quantities (X and Y) required to express present target position in Cartesian coordinates.

Resolver BR-1 solves the following equations: R CosE = Rh and R SinE = Rv. Resolver BR-2 solves the following equations: Rh CosBy = Rhy and Rh SinBy = Rhx.

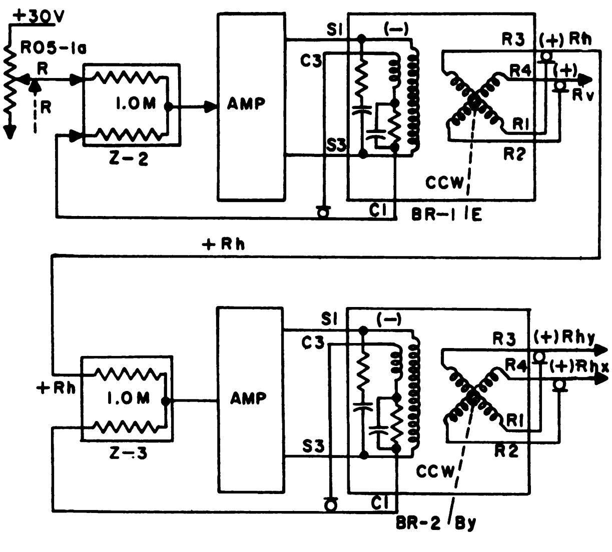


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Figure 2-36.—Typical resolver chain for converting polar coordinates into rectangular (cartesian) coordinates.

## Composition

Another trigonometric function a resolver handles is the composition of a vector. This is the process of taking a vector in its rectangular form and composing the vector in its polar form. In other words, two sides of a right triangle are known and the resolver solves for the hypotenuse and acute angle. To accomplish composition with a resolver, both stator windings are energized. These inputs represent the height and base of the triangle. One electrical output and one mechanical output will be obtained. These outputs represent the hypotenuse and acute angle. To obtain a mechanical output from a resolver, one rotor winding provides the input signal to a servomechanism that drives the rotor of the resolver until zero volts is induced in the winding. When this operation is complete, the resolver loop has composed the vector. The position of the rotor represents the angle of the vector, and the other rotor output represents vector magnitude.

The loop shown in figure 2-37 is used to change rectangular coordinates of target motion to a vector quantity, thus representing target course (direction) and speed (magnitude). The two motion coordinates, DMhy and DMhx, are computed with respect to the N-S and the E-W axis, respectively. A resolver is used to compose these coordinates into a vector, which has target course Ct as its direction and target speed DMh as its

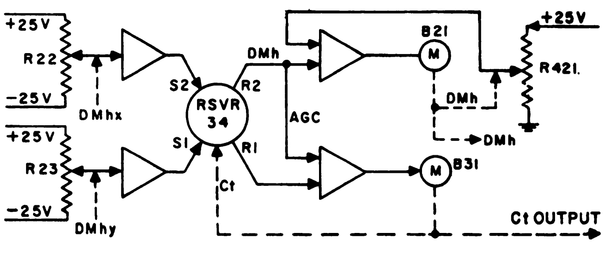

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Figure 2-37.—Vector composition.

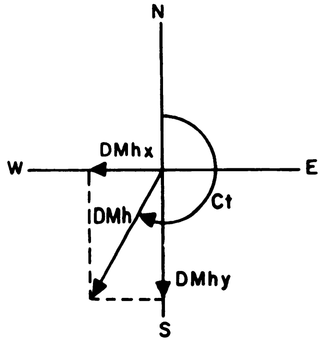

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**Figure 2-38.—Geometry of rectangular to polar transformation (the composition of vector components).**

magnitude. Figure 2-38 shows the geometry of the problem.

Returning to figure 2-37, potentiometers R22 and R23 are energized with +25 and −25 volts, since target rates (DMhx and DMhy) are either plus or minus quantities. A target course of zero degrees is computed when the output of R22 is zero volts and R23 has a negative output.

To compute a target course of 45°, assume that the output of potentiometers R22 and R23 is −15 volts. Servomotor B31 will drive the rotor of resolver 34 counterclockwise until a null voltage is induced in the R1 winding. Concurrently, the voltage induced in the R2 winding will be a maximum negative voltage, or −21.21 volts.

To provide the above outputs, the voltages induced in R1 and R2 must follow an established equation in each rotor winding. These equations are

$$R1 = -DMhx(CosCt) + DMhy(SinCt)$$

$$R2 = -DMhx(SinCt) - DMhy(CosCt).$$

The voltages induced in R1 (fig. 2-39) will subtract; therefore, the mechanical position of the rotor represents the angle of the target course vector. The voltages induced in R2 will add; therefore, the magnitude of the R2 voltage represents target speed DMh. A servomechanism is used to obtain a mechanical representation of target speed. Automatic gain control is provided to the Ct servomechanism so that the gain of the amplifier varies inversely with the target speed.

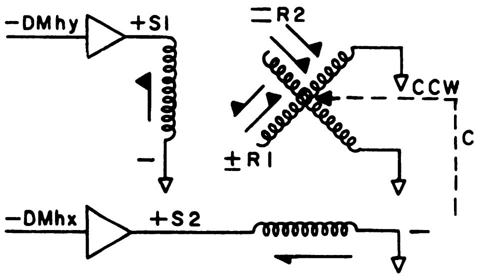

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**Figure 2-39.—Polarity of rotor windings (R1 and R2) of B34.**

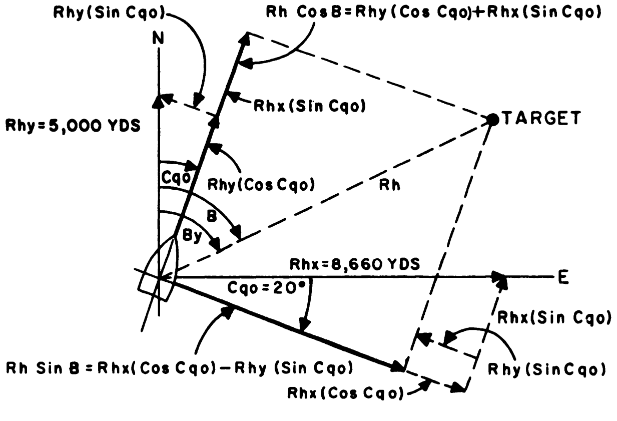

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**Figure 2-40.—Geometry of a coordinate rotation problem.**

Another trigonometric function a resolver can handle is the rotation of coordinates. This process involves the rotation of rectangular coordinates from one axis system to another axis system.

To rotate coordinates from one axis system to another, a resolver must have one mechanical input and two electrical inputs. Two electrical outputs are obtained.

The geometry of a coordinate rotation problem is shown in figure 2-40. Target position is expressed by rectangular coordinates Rhx and Rhy. These quantities relate how far the target is from own ship, measured along the N-S and E-W axis. The problem is to express target position in rectangular coordinates with respect to the centerline of own ship; or in other words, to determine the distance to the target along and perpendicular to own-ship centerline. Actually, the quantities desired are the rectangular coordinates of the relative target bearing vector. The quantities Rhx, Rhy, and Cqo are given in figure 2-40.

To solve the two equations, Rh CosB = Rhy (CosCqo) + Rhx(SinCqo) and Rh SinB = Rhx (CosCqo) − Rhy(SinCqo), two resolvers are used. (See fig. 2-41.) Horizontal range Rh and true target bearing By are the inputs to resolver B1 that resolve the polar vector into rectangular coordinates, Rhx and Rhy. The equations solved by resolver B1 are Rhx = Rh SinBy and Rhy = Rh CosBy. The magnitude of Rhx and Rhy are +8.66V and +5V, respectively.

The rotor of resolver B2 is rotated by ships heading Cqo, and the stators are energized by Rhx and Rhy—stator S5 by Rhx and S6 by Rhy. If ship heading were 0°, resolver B2 would compute the rectangular coordinates of the polar vector; that is, the R1 output would be +5 volts and the R2 output would be +8.66 volts. However, ship's heading is 20°; therefore, the R1 output increases while the R2 output decreases. The equations solved by resolver B2 are

R1 + Rhy(CosCqo) + Rhx(SinCqo)

5V(.9397) + 8.66V(.342)

4.70V + 2.96V

+ 7.66V

R2 = Rhx(CosCqo) − Rhy(SinCqo)

8.66V(.9397) − 5V(.342)

8.14V − 1.71V

+ 6.43V.

The R1 and R2 voltages are the rectangular coordinates of the relative target bearing vector Rh and B and are measured along and perpendicular to own-ship centerline. Hence, the R1 voltage represents Rh CosB, and the R2 voltage represents Rh SinB.

**Inverse Sine and Cosine Loops**

A resolver can be used in a loop to solve for an angle, given the sine or cosine of that angle. Such a loop is shown in figure 2-42, and it consists of a resolver, a network box, and a servomechanism.

In this loop, the rotor of the resolver is driven by the servomechanism, whose mechanical output is the computed angle θ. If the R2 voltage is not equal and of opposite phase to the Sin input voltage, a signal to the servomechanism will cause it to drive the rotor until it becomes equal.

Since the resolver stator is supplied with a constant voltage, the R2 voltage is at all times proportional to the sine of the computed angle; that is, R2 = 10V × sine of the computed angle. The R1 voltage is at all times proportional to the cosine of the computed angle; that is, R1 = 10V × cosine of the computed angle.

In other words, the resolver loop solves for angle θ when the hypotenuse (10 volts) and the height (Sin θ input voltage) are known. Assume that the Sin θ input voltage is +5 volts and that the resolver is energized by a constant +10 volts. The servomechanism will drive the rotor until the output of R2 is −5 volts, at which time the loop will stop driving. The resolver rotor must be rotated clockwise through a 30° angle to produce this output. The R1 output at this position of the

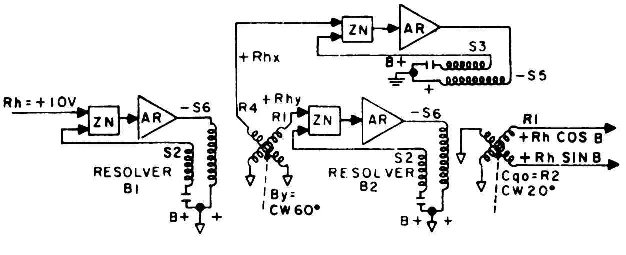

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Figure 2-41.—Rotation of rectangular coordinates with resolvers.

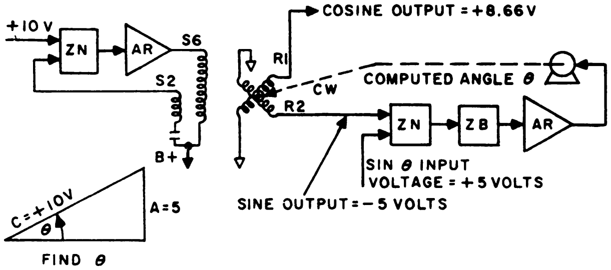

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Figure 2-42.—Inverse sine resolver loop.

rotor is +8.66 volts. If the Sin $\theta$ input voltage were changed to 3.42 volts, the resolver would solve a 20° angle. If the Sin $\theta$ input voltage were +8.192 volts, the resolver would solve a 55° angle.

The resolver loop can be made to function as an inverse cosine loop by selecting the rotor lead R1 as the input to the network box. By necessity, the other input to the network box would have to be a voltage that represents the cosine of the angle desired. The inverse cosine loop is shown in figure 2-43. Operation of the loop is the same as that discussed for the inverse sine loop, except the two known parts of the triangle to be solved are now the hypotenuse and adjacent side.

If the Cos $\theta$ input voltage were −8.66 volts, the resolver loop would solve a 30° angle. The R2 output voltage would be −5 volts. If the Cos $\theta$ input voltage were −9.397 volts, the resolver loop would solve a 20° angle; the R2 output would solve a 50° angle, and the R2 output would be −7.660 volts.

Note that only one stator winding of the resolver is energized in either loop. Thus, the hypotenuse of the triangle is represented by the input voltage to the resolver.

## RATE COMPUTING LOOPS

To solve the fire control problem, rates of target motion relative to own ship must be determined. This is done by comparing the rates of change of stabilized rectangular coordinates, such as Rhx, Rhy, or Rv, with corresponding rates generated by the computer. Then, the generated rates are corrected until they agree with the rates of change of the measured coordinates. The correct target motion rates are established for use in prediction. This corrective process is called *rate control.* Figure 2-44 shows a rate loop for computing DMhx, the rate of linear motion along the East-West axis referenced to the horizontal plane. The loop has two inputs, time and the present Rhx. The time input drives the disc of a ball and disc integrator at a constant speed. The integrators other input is the present DMhx, which positions the ball section. The output i(Rhx) is the increment of Rhx for the time input. The quantities i(Rhx) and j(Rhx) are added to produce the computed Rhx value c(Rhx). The Rhx input to the loop is compared with the computed value and the result Rhx-c(Rhx) is applied to offset the rotor of the CT. The output of the CT feeds the servo loop, which drives to return the CT to a null condition. The output of the rate loop, DMhz, is sent to the prediction section for computing Rhx2 and other quantities.

## OPERATIONAL AMPLIFIERS

Previously we have discussed using summing amplifiers in a variety of applications, ranging from algebraic summation to multiplication and division. A summing amplifier is nothing more than an operational amplifier (op amp). The amplifiers previously discussed used negative feedback to produce linear gain and prevent saturation or overdriving. Operational amplifiers (op amp) can be used with different feedback schemes that produce different effects. Nonlinear

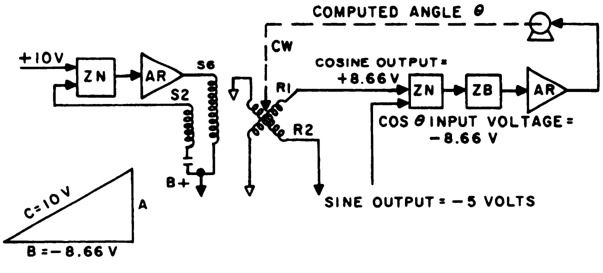

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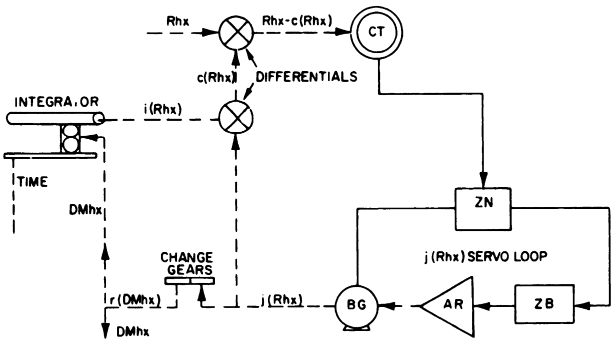
Figure 2-43.—Inverse cosine resolver loop.



55.320

Figure 2-44.—DMhx rate loop.

and even positive feedback are also used with op amp to produce different functions.

Most operational amplifiers are now packaged as an integrated circuit (IC). The general purpose op amp, with a few variations in external components, can be configured to perform the following functions:

1. General purpose amplification
    a. Inverting amplifier (low-impedance signals)
    b. Noninverting amplifier (high-impedance signals)
    c. Unity-gain inverter (voltage follower)
2. Analog-computer elements
    a. Summing amplifier (previously covered)
    b. Integrator (solution of differential equations)
    c. Differentiator (for pulse peaking)
    d. Logarithmic amplifier
    e. Multiplier and divider amplifiers
3. Miscellaneous uses
    a. Linear rectifier (low-level ac signals)
    b. Active filters (low-pass, high-pass, etc.)
    c. Sine wave oscillator circuits
    d. Multivibrator circuits
    e. Function generator (square-wave, sine-wave, sawtooth, and pulse generation)
    f. Analog-to-digital and digital-to-analog conversions

The ability to readily change the application by changing only a few external components has made the versatile op amp a very common electronic component in current fire control systems. Other characteristics that contribute to the wide use of op amps are as follows:

- High gain
- High input impedance (minimum loading)
- Wide bandwidth
- Low noise figure

**Logarithmic Functions**

As previously mentioned, op amps can be readily converted to perform nonlinear functions. One of the most useful nonlinear functions in electronics is the logarithm. Using logarithmic functions, multiplication and division are reduced to simple addition and subtraction. A more complex operation, such as increasing a number by a power, is reduced to multiplying the log of the number by the power. Logarithms are used extensively when expression of gain or loss in a circuit is needed. For additional study on logarithms, refer to *Mathematics*, volumes 1 and 2, NAVEDTRA 10069 and 10071.

A linear op amp can be combined with a nonlinear device, such as a pn junction, to achieve a very useful nonlinear device called a logarithmic amplifier, as shown in figure 2-45. By putting a common base configured transistor in the feedback path for the op amp, a variable resistance (pn junction) replaces the feedback resistor. The base-to-emitter junction current of Q1 varies exponentially with the signal amplitude; therefore, the feedback (collector current) varies exponentially. The exponential relationship produces a logarithmic function in the output voltage; Eout = Log E in. Capacitor C1 and resistor R2 are used to decouple the output from the input and improve the accuracy of the exponential function. This configuration does have a drawback, the feedback loop (Q1, R2, and C1) provides gain that degrades the frequency stability and decreases the frequency response at lower signal levels.

Frequency stability can be achieved by improving the phase compensation (decoupling). In figure 2-45, phase compensation produced decoupling at a linear rate. By changing the decoupling configuration to produce nonlinear

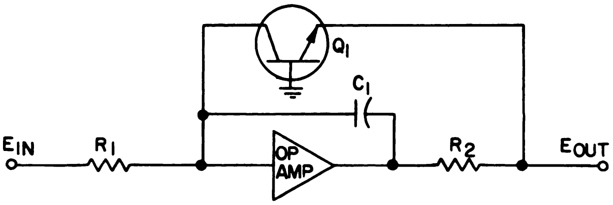


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Figure 2-45.—Logarithmic amplifier.

decoupling, frequency stability can be obtained. In figure 2-46, a diode ($D_1$) is added and $R_2$, from figure 2-45, is replaced with two resistors ($R_2$ and $R_3$). Now $R_2$, $R_3$, and $D_1$ make a T network. Diode $D_1$ has a variable resistance function the same as the pn junction in the transistor. The variable decoupling now produces a very accurate logarithmic amplifier.

Using a logarithmic amplifier with a summing amplifier can easily produce the product of two or more quantities. The only thing needed now is a circuit to convert the log values back to a nonexponential value. This can be accomplished by what is appropriately called an antilog amplifier. Figure 2-47 shows how easily this is accomplished by relocating the nonlinear component ($Q_1$) to the input circuit instead of the feedback loop. $R_1$ is now the feedback resistor, and the op amp is in a summing amplifier configuration. $Q_1$ now changes the input signal exponentially that results in a linear input to the op amp.

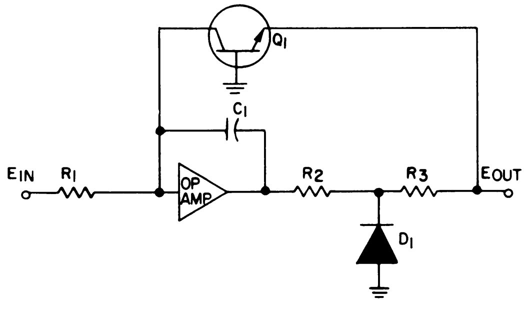

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Figure 2-46.—Improved logarithmic amplifier.

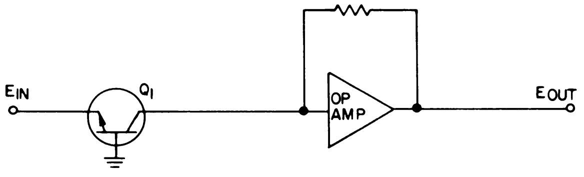

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Figure 2-47.—Antilog amplifier.

## SUMMARY

The fundamental characteristic of an analog computer is similar to the subject in some areas; for example, it duplicates the geometry, dynamic behavior, or some other aspect of the subject. The basic operating principle of an analog computer is continuous measurement of quantities.

Analog computing elements can be employed in weapons and fire control systems wherever problems of calculations from continuous data, simulation, or control are encountered.

This continuous calculation requires that the fire control computer be designed for a particular system, which reduces its versatility. Analog fire control computers are *not* general purpose computers. Several quantities are continuously measured in the fire control system (such as range, bearing, and elevation of the target) and always applied to the same inputs of the analog computer. Inside the computer, the manipulations are continuously performed, and the results are continuously available as outputs, to be fed where needed.

- SCALE FACTORS are constants that relate computational variables directly to the problems being solved. The formula is

$$\text{SCALE FACTOR} = \frac{\text{ANALOG UNITS}}{\text{EQUATION UNITS}}$$

where the analog units are usually shaft revolutions or volts, and the equation units are usually in degrees, yards, feet, knots, or some other quantity. The larger the scale factor, the more accurate the solution of the problem. Nevertheless, accuracy is limited by the voltage range required or the feasible gear ratios used in the construction of the computing elements.

- ELECTROMECHANICAL COMPUTING ELEMENTS include potentiometers, synchros, resolvers, and generators. These elements contain both electrical and mechanical parts and perform mathematical functions.

- POTENTIOMETERS, also called pots, are basic analog computing elements. They are used for multiplication, division, and generation of nonlinear functions such as sine, cosine, secant, and so forth. A potentiometer is a variable voltage source that multiplies a mechanical motion times an electrical input.

Potentiometers can be found in a wide range of styles. The basic pot has less than 360° of rotation (about 324°). Other pots are full 360° rotation, double-ended, multi-turn, and have nonlinear functions.

- RATE GENERATORS are also known as tachometers. Rate generators change a mechanical (speed) motion into electrical information. Rate generators can produce either an ac or dc voltage. They are used in computations and servo loops.

- PARALLEL RESISTOR NETWORKS (also called network boxes) are used to provide the algebraic sum of two or more electrical inputs. The networks do not provide an actual sum but a proportional sum. This is a scale change that can be compensated for by the addition of a summing amplifier to prevent loading and restore the input scale if desired.

- SUMMING OPERATIONS use the network boxes and summing amplifiers with exactly 180° phase shift from input to output. The summing amplifier and network box form a summing loop. The summing amplifier has a high gain (up to 20,000:1) that is held constant by negative feedback. The amplifier has a high input impedance that reduces loading of the network boxes and maintains the accuracy of the summing operation. Summing loops can be used to sum voltages of either the same or dissimilar scale factors.

- MULTIPLICATION AND DIVISION OPERATIONS can be either a simple multiplication of a variable voltage by the mechanical motion of a potentiometer wiper or used as summing loops with the potentiometers. Division operations are performed by using a potentiometer to vary the feedback, and, thus, the gain of a summing amplifier.

- SERVO MULTIPLIERS are used to multiply two voltages together with the output as a voltage. This is accomplished by first converting one voltage into a proportional mechanical rotation using a servo. This mechanical motion produces the final multiplication by the use of ganged potentiometers.

- TRIGONOMETRIC FUNCTIONS can be accomplished with potentiometers, but a more accurate and versatile device known as a resolver is the primary device used. Resolvers can be connected to perform any of the trigonometric functions needed for the resolution of right triangles and coordinate rotation.

- RATE COMPUTING LOOPS perform a process known as rate control. They establish the rate of change of the input and compare the output against the input determining the acceleration or deceleration. The rate computing loops are primarily used in predicting future target position in fire control computers.

- OPERATIONAL AMPLIFIERS can be found in many configurations. op amps are versatile and found in wide use in analog computers. They are sometimes called by the function they perform; summing, isolation, logarithmic, and so forth. Op amps are characterized by having high gain, high input impedance, wide bandwidth, and a low noise figure.

Now that we have studied analog computing elements, you should have a better understanding of how analog computers perform their computations. In the next chapter, you will study digital computers and their application to fire control.

# CHAPTER 3

# DIGITAL COMPUTERS

The computer can be considered as the heart of the fire control system (fig. 3-1). All modern-day fire control systems have a computer. Some systems have the older analog computer as the fire control computer, while the newer systems have the digital computer as the fire control computer.

The function of the computer in the fire control system, whether it be analog or digital, is the same—to solve the fire control problem and coordinate the overall functioning of the fire control system. However, the digital computer has certain advantages over the analog computer, which makes it more suitable to fire control. One of the main advantages is the ability of the digital computer to solve more than one problem at a time, whereas the analog computer cannot switch from one problem to another without losing computation time. Analog computers are better suited to handling single problems involving continuous quantitative computation, while digital computers

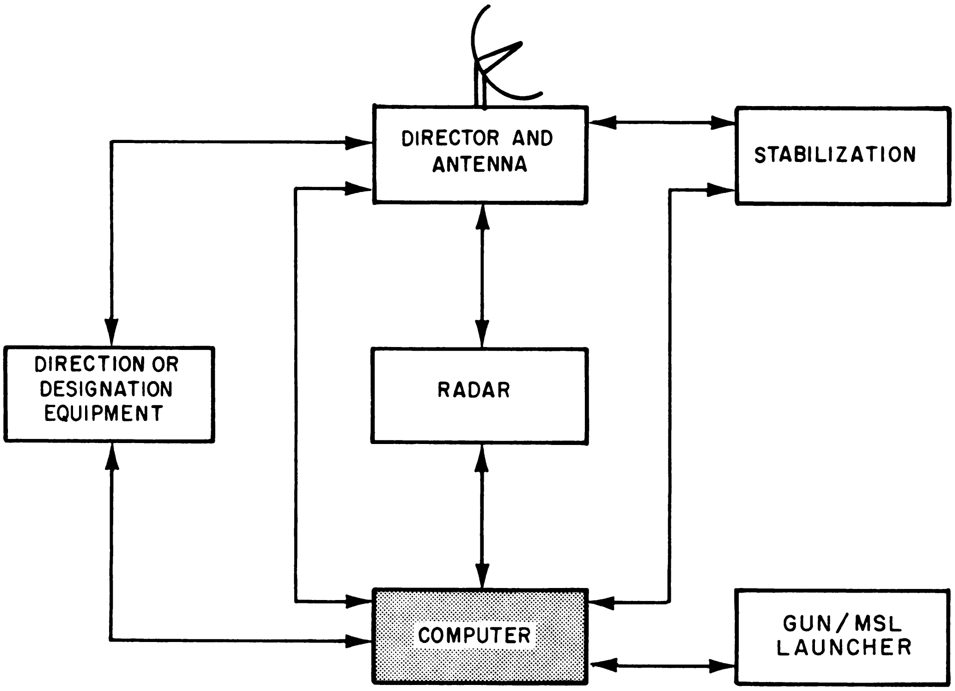

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Figure 3-1.—Basic fire control system.

are better suited to handling multiple problems involving logical decisions.

## INTRODUCTION TO DIGITAL COMPUTERS

A computer is any device capable of accepting information, applying mathematical operations to that information, and obtaining results of these operations. Therefore, a computer must have an input, processing, and output section.

Before any problem can be solved by a computer, the quantities involved must be expressed in terms of common units; that is, digital computation is the process in which digits alone are used to solve the problem.

Basically, the purpose of a digital computer is the same as that of any other computational aid. However, it is more accurate within practical limits of speed. Computers can perform thousands of repetitive computations involving hundreds of thousands of digits without making an error. Further, they can store millions of items of information for future use.

Digital computers also have limitations in that a continuous variable cannot be processed. Simple and explicit instructions (programming) must be provided for each operation that is to be performed. Instructions, as to where information is stored, how to use it, what to do with it, and what step is required next, are sometimes more complicated than the problems for which the computer is used to solve. Approximations and rounding off are also problems encountered with computers.

A digital computer performs its calculations by counting and comparing. With this simple capability, it can add, subtract, multiply, divide, and make logical decisions. Therefore, to perform computations with a digital computer, all that is needed is a method that enables the machine to count, compare, and transfer a digit from one place to another.

In addition to the analog versus digital classification just mentioned, computers can also be classified according to the purpose for which they are intended. A *special-purpose computer* is one intended to solve one problem or a predetermined small number of problems. It is usually connected permanently. A *general-purpose computer* is one intended for a variety of applications. It is normally programmed for each individual application.

In the past, problems in the fire control field were solved by special purpose computers. However, the advent of the digital computer has changed this. General-purpose digital computers are used widely aboard Navy ships in weapon system applications.

You, as an FC2, will encounter digital computers during your career. The two most widely used computers that you will deal with are the Mk 152 and the AN/UYK-7(V) digital computers.

In this chapter we will discuss both computers at the block diagram level. If you have not done so already, it would be to your advantage to stop here and study *NEETS Module 13* (NAVEDTRA 172-13-00-83) and *Digital Computer Basics* (NAVEDTRA 10088-B1) before continuing in this manual. In other words, you should already know the basics of computers to understand fully the material in this chapter.

## DIGITAL COMPUTER MK 152

Computer Mk 152 (UNIVAC 1219B Military Computer) is a medium-scale, general-purpose, digital computer that is specifically designed to comply with the environmental specifications required for shipboard installations. The computer is a real-time computer, which uses a stored program and is capable of solving any problem normally solved by standard mathematical techniques. It also performs most data processing functions.

To meet the extreme requirements of real-time processing operations, the computer is equipped with three distinct memory areas. These are main memory, control memory, and a 32-word (18-bit) bootstrap memory. The nondestructive feature of the bootstrap memory provides for the storing of constants and instructions that permit the automatic recovery from fault situations and the initial loading of routines.

With its high operating speed (2-microsecond main memory cycle time) and 500-nanosecond (cycle time) control memory, the computer is capable of transferring 500,000 words per second. Arithmetic and input/output operations are performed using single-length (18-bit) or double-length (36-bit) words where greater precision is required for compatibility with other computers. A repertoire of 102 instructions allows complete programming freedom in mathematical and logic computations, as well as full control of input/output buffer transfers and of real-time, on-line operations. The computer features parallel transfer, one's complement binary arithmetic, direct addressing, and program-controlled automatic address or operand modification through eight control memory-contained index registers.

## PHYSICAL DESCRIPTION

The computer is housed in a single cabinet and is self-sufficient except for required input power and data signal lines. The standard computer cabinet (fig. 3-2) is subdivided into four drawers, a power supply, two fan assemblies, and various panels necessary for operation/maintenance, control, and input/output connections. All drawers, chassis, and assemblies mounted within the control unit frame assembly may be removed for maintenance or repair if required. An alternate cabinet configuration is supplied when 12 or 16 input/output channels (optional) are selected with identical drawers A1 and A8 (fig. 3-3). Actual configurations are dependent upon system application.

Drawer assemblies A1, A2, A4, and A8 contain the necessary circuitry for the control of various computer instructions and transfers. The A3 drawer assembly contains computer core memory and associated circuitry. The power supply produces dc voltages used throughout the control unit cabinet. A power control panel (A5) is provided to allow for the complete control of the computer from a single panel during the turn-on and turn-off sequences. Abnormal conditions are indicated by audible and visual alarms.

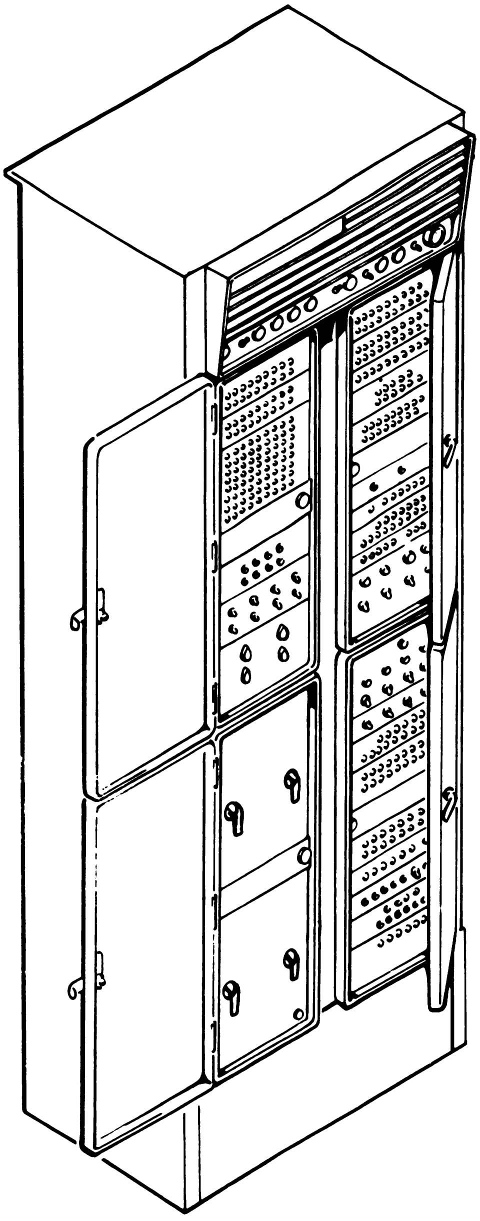

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Figure 3-2.—Computer with maximum of eight input/output channels.

## FUNCTIONAL DESCRIPTION OF COMPUTER MK 152

Computer Mk 152 is divided into four functionally definable sections: control, arithmetic,

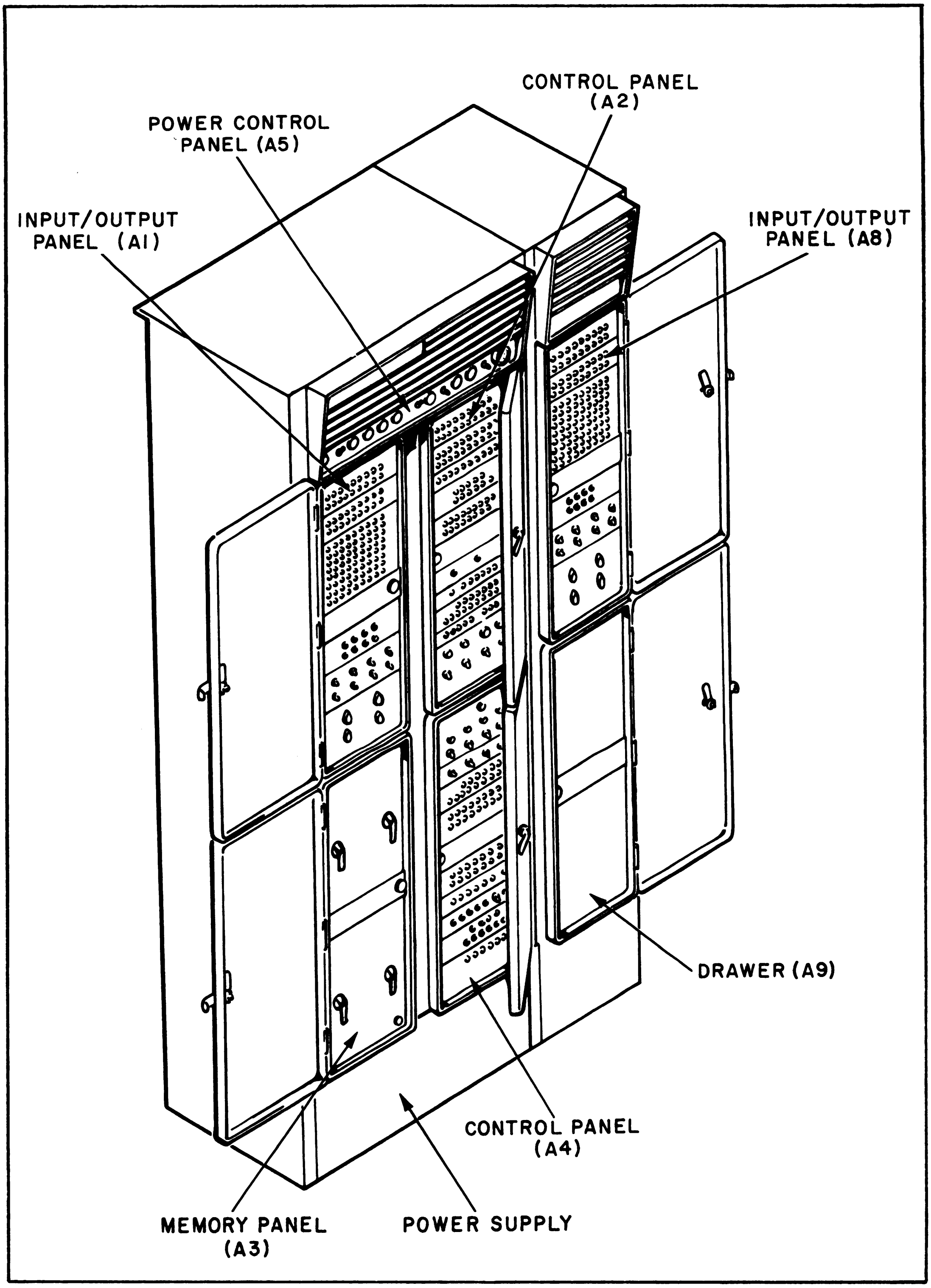

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Figure 3-3.—Computer with maximum of 16 input/output channels.

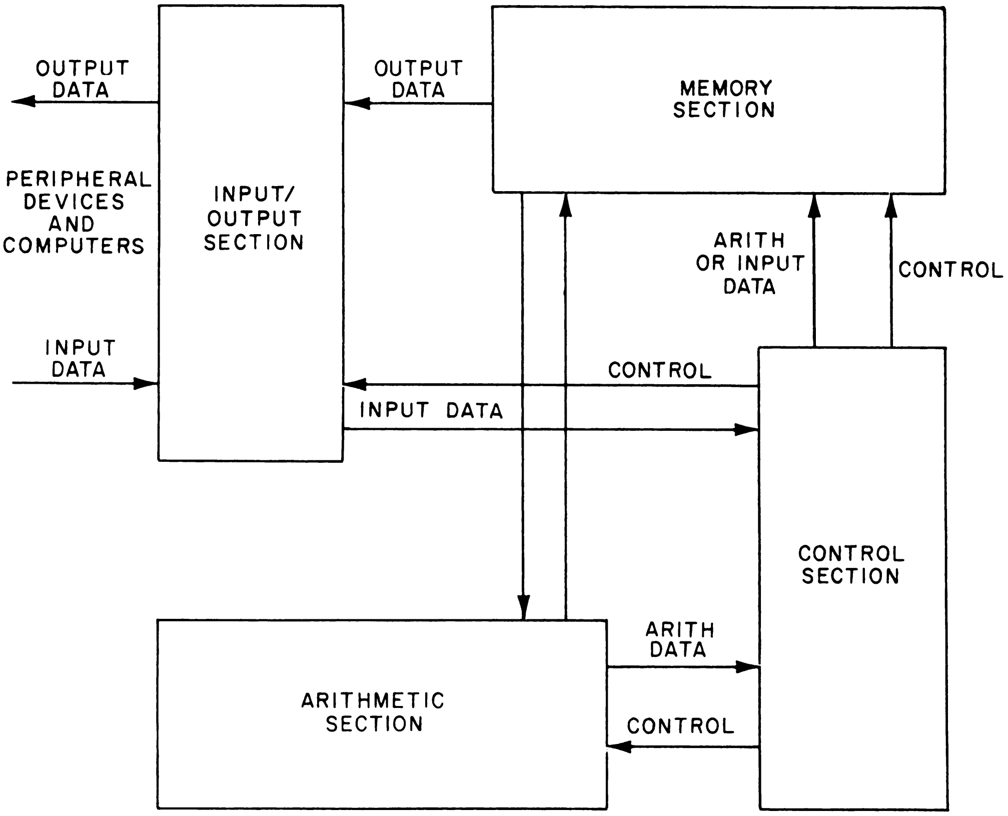

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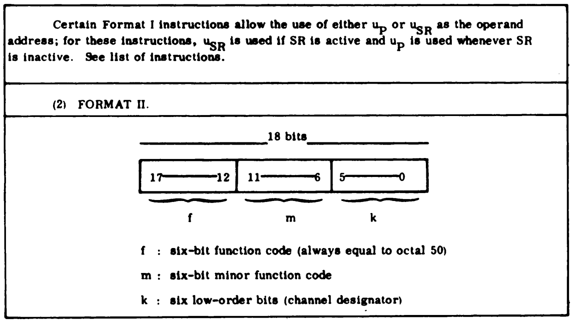
**Figure 3-4.—Computer simplified block diagram.**

memory, and input/output (fig. 3-4). We will describe these functional areas in detail as we proceed through this chapter.

The computer has a repertoire of 102 flexible, single-address instructions with provisions for address or operand modification by eight index registers. (Single-address instructions contain a coded representation of the operation to be performed and a single address of a word in storage or an operand. The instructions of the single address code contain a maximum of one address for reference in storage.) In our discussion, we will refer to these instructions by their operational name and functional designator. The instructions are classified as either format I or format II instructions.

Format I instructions (fig. 3-5, view A) contain a 6-bit function designator and a 12-bit operand. The function designator specifies the particular operation to be performed, and it can be expressed in octal. Within the computer, it is in binary. The operand specifies either a constant or part of a memory address to be used in the performance of an instruction.


Certain Format I instructions allow the use of either $u_P$ or $u_{SR}$ as the operand address; for these instructions, $u_{SR}$ is used if SR is active and $u_P$ is used whenever SR is inactive. See list of instructions.

(2) FORMAT II.

f : six-bit function code (always equal to octal 50)
m : six-bit minor function code
k : six low-order bits (channel designator)

180.76

**Figure 3-5.—Computer instruction format.**

Format II instructions (fig. 3-5, view B) contain a 6-bit function designator and a 6-bit minor function code. The function designator is always an octal 50 (to specify a format II instruction). The minor function code is used to identify the instruction to be performed. The low-order, 6-bit designator of the instruction word identifies a count during a shift operation, a channel number for input or output functions, or a switch setting for stop or skip instructions.

The computer has an automatic program recovery capability. In the event of a computer fault, address 500 is referenced to automatically load a new program into the computer memory.

The computer has provisions for remote control and monitoring. A remote control console can be connected to the computer by a standard input/output cable plugged into the special remote console jack. A front panel indicator shows whether the computer is in local control or remote control. The indicators and alarm on the remote control console are functional when the computer is in local or remote mode. The switches on the remote control console are functional only when the computer is in remote mode.

### Memory Capacities and Special Addresses

The computer memory presently can be expanded to 65,536 (base 10) 18-bit words of addressable storage locations divided physically and functionally into three distinct sections. The capacities of the various computer modifications are dependent upon system requirements that vary. (Our discussion will assume 65,536 storage locations.) The three sections of memory are a 128- or 256-word optional control memory, a 32-word nondestructive readout (NDRO) bootstrap memory, and main memory.

**CONTROL MEMORY.**—Control memory is an independent high-speed, word-oriented core memory (cycle time 500 nanoseconds) used for index registers, buffer control words, real-time clock cells, real-time clock interrupts, and the fault interrupt address. The fixed addresses for these functions and channel designations, expressed in octal, are as follows:

| Address | Assignment |
|---|---|
| For computers with eight I/O channels: | |
| 00000 | Fault interrupt entrance register |
| 00001-00010 | Eight index registers |
| 00011 | Resume fault interrupt entrance register |
| 00012 | Real-time clock monitor interrupt entrance register |
| 00013 | Real-time clock overflow interrupt entrance register |
| 00014 | Real-time clock monitor word register |
| 00015 | Real-time clock incrementing register (RTC word register) |
| 00016 | Synchronizing interrupt entrance register |
| 00017 | Scale factor shift count word register |
| 00020-00037 | Continuous data mode (channels 0-7) or external function buffer control registers (0-7) |
| 00040-00057 | Output buffer control registers (channels 0-7) |
| 00060-00077 | Input buffer control registers (channels 0-7) |
| For computers with 16 I/O channels: | |
| 00200-00217 | Unassigned |
| 00220-00237* | Continuous data mode (channels 10-17) or external function buffer control registers (10-17) |
| 00240-00257* | Output buffer control registers (channels 10-17) |
| 00260-00277* | Input buffer control registers (channels 10-17) |

(*When not assigned for these functions, the locations may be used for data storage.)

**NDRO BOOTSTRAP MEMORY.**—The computer is provided with 32 nondestructive readout memory locations $00500_8$-$00537_8$, which contain computer instructions and constants for an initial load program (bootstrap). This provides the ability to enter an initial package of utility routines that may be used to load and/or debug more sophisticated programs. These memory locations have unique characteristics in that they are transformer cores that operate in a special type of nondestructive readout mode (read-only memory). They are not accessible to the programmer for store-type instructions.

Bootstrap (NDRO) memory may be locked out by activating the bootstrap mode switch on the console. If the bootstrap memory is locked out, addresses $00500_8$-$00537_8$ in main memory are then available for other programming requirements.

**MAIN MEMORY.**—The main memory consists of core storage that is used for program, constants, and data storage. Main memory maximum capacity is 65,248 or 65,376 (18-bit) storage locations, dependent upon the optional control feature. Word transfer time (cycle time) is 2-microseconds. All locations are accessible to the programmer at random and to all sections of the computer on a time-shared basis. Some locations are given special assignments, which the programmer must respect and provide for their contents. The fixed addresses (in octal) assigned to main memory are as follows:

| Address | Assignment |
|---|---|
| 00100-00117 | External interrupt registers (channels 0-7) |
| 00120-00137 | External function monitor registers (channels 0-7) |
| 00140-00157 | Output monitor registers (channels 0-7) |
| 00160-00177 | Input monitor registers (channels 0-7) |
| 00300-00317 | External interrupt registers (channels 10-17) |
| 00320-00337 | External function monitor registers (channels 10-17) |
| 00340-00357 | Output monitor registers (channels 10-17) |
| 00360-00377 | Input monitor registers (channels 10-17) |
| 00400-00477* | Assigned to expanded ESI option when selected; otherwise instruction word and data storage |
| 00540-00577 | Instruction word and data storage |
| 00600-00677* | Assigned to expanded ESI option when selected; otherwise instruction word and data storage |
| 00700-177777 | Instruction word and data storage |

(*These addresses are in control memory when 256 words of control memory are used.)

### Computer Registers

All registers in the computer may be classified as addressable or nonaddressable. Addressable registers (table 3-1) are directly available to the programmer through computer instructions. The other functional registers are nonaddressable. We will describe the register functions as we discuss the operations of the various computer sections. Let's begin with a functional analysis of the computer control section.

### Control Section

The control section (fig. 3-6, a foldout at the end of this chapter) contains circuitry necessary to procure, modify, and execute the single address instructions of a program stored in the core memory of the computer. It controls parallel transfers of instructions and data. Direct or indirect addressing capabilities and automatic address and operand modification are directed by the control section translators and the timing of a synchronous electronic master clock. This section controls all arithmetic, logical, and sequential operations of the computer except those assigned to the input/output section. It has facilities to permit an interruption of the running program when certain real-time events necessitate interventions.

The control section provides the timing, instruction translation, and operational sequencing required for performance under either program control or manual operation. Under program control, the computer performs the instructions

Table 3-1.—Registers

| Designator | Size Bits | Function |
|---|---|---|
| Addressable | | |
| A | 36 | Arithmetic Accumulator (consists of registers AL and AU) |
| AU | 18 | Accumulator, Upper |
| AL | 18 | Accumulator, Lower |
| B | 18 | Data Transient (used in incremental and decremental operations) |
| ICR | 3 | Index Control Register |
| P | 16 | Program Address |
| SR | 5 | Special Register |
| Nonaddressable | | |
| $B_u$ | 18 | Transient Register (multipurpose) |
| CE | 18 | Output Buffer, Channels 0, 2, 4, and 6 |
| CO | 18 | Output Buffer, Channels 1, 3, 5, and 7 |
| CE' | 18 | Output Buffer, Channels 8, 10, 12, and 14 |
| CO' | 18 | Output Buffer, Channels 9, 11, 13, and 15 |
| D | 18 | Data Transient (holds and operand for the adder during arithmetic operation) |
| F | 7 | Function Register (holds the function code of the instruction being executed) |
| $S_1$ | 16 | Storage Address, Main |
| $S_0$ | 8 | Storage Address, Control |
| W | 18 | Auxiliary Arithmetic (shifting register) |
| X | 18 | Exchange Transient |
| Zm | 18 | Storage Transfer, Main |
| Zc | 18 | Storage Transfer, Control |
| K | 6 | Counter |

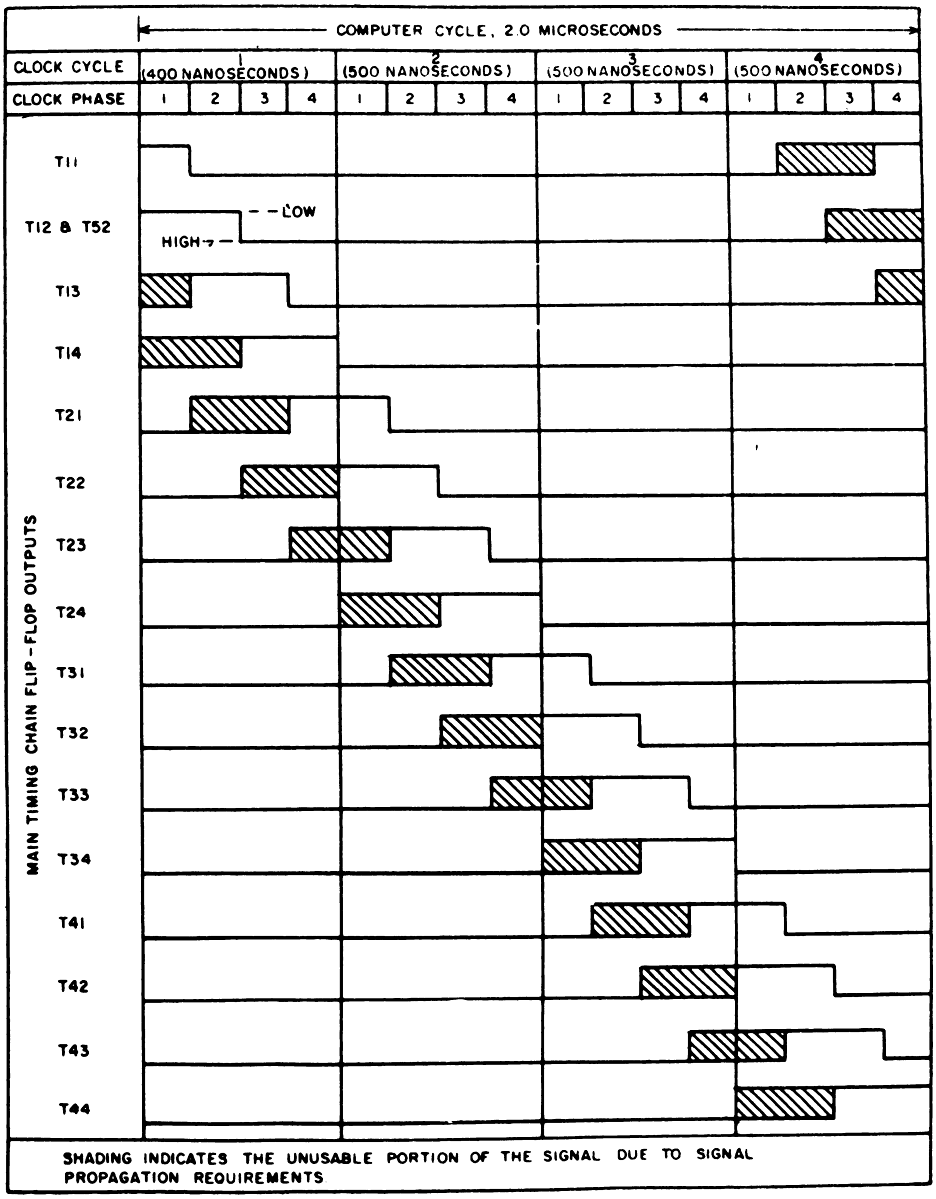
180.77

of an entire program at a high rate of speed, stopping only where programmed. For manual operation, two control panels (located on drawers A2 and A4) (fig. 3-3) contain the switches and indicators by which the computer may be sequenced through the functions of an instruction, allowing each operation and its results to be visually displayed and examined.

The control section of the computer consists of five logically definable areas: console control, timing, program translation and control, registers, and special circuits. We will discuss these areas shortly. Before doing so, however, let's examine the computer's concurrent processing capability.

**REAL-TIME PROCESSING.**—The ability of the computer to process various applications concurrently is implemented by a program intervention system called *interrupts*. These interrupts may originate at some remote external device (*external interrupts*) or they may originate within the computer (*internal interrupts*) as a result of program requests. Since more than one may occur at the same time, the computer possesses a priority scheme with decision-making qualities so that it can select the branch of operation for solving the problem requiring the most urgent attention. Under program control, the other interrupts may be honored in turn according to the next highest priority, or they may be ignored. With this *interrupt* feature, real-time problem solution and maximum processing potential of the system are realized, since less important routines can occupy the computer's surplus time.

The master clock in the computer controls and synchronizes all operations performed by the various sections through the electronic timing chains allotted to them. The read/write cycle time of main memory is 2-microseconds (fig. 3-7). All



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180.79

Figure 3-7.—Main timing cycle outputs.

control and timing sequences for the various functions the computer performs are based on this 2-microsecond cycle. Four 500-nanosecond control memory read/write cycles occur during one main memory read/write cycle. An instruction from main memory storage can be transferred to the control section for execution in approximately 0.9 microsecond. Any modification to this instruction and complete translation are completed before the end of that main memory cycle, since the modifiers are extracted from control memory in less than 250 nanoseconds. The input/output section has independent access to control memory for its control words, clocks, and so forth, during instruction sequences. Let us, at this time, take a closer look at computer timing.

**TIMING.**—Timing commands within the computer are a function of the master clock circuit and the main timing cycle circuits. The master clock circuit produces four basic timing pulses used to establish the operation of the main timing cycle circuits and provides command enable pulses through gating by the main timing chain. The master clock generates and distributes four basic timing pulses for each 500 nanoseconds of operation. These four pulses, called phases (01, 02, 03, 04), constitute one complete clock cycle. Each phase pulse duration time is approximately 125 nanoseconds. Four clock cycles constitute one computer cycle of 2 microseconds. Figure 3-7 shows the relationship between the master-clock phase-pulse output and the outputs from the main timing chain flip-flops.

The main timing chain supplies enables to the computer logic circuits for operation of command timing sequences. Timing pulses developed by command timing sequences are numerically identified by the clock cycle and phase with which they are associated. For example, in the term *T34*, the 3 represents the third clock cycle, the 4 indicates that phase four is the last usable phase occurring during that timing pulse. The only exception to this rule is T52. It is used only during complement A and complement AL instructions.

**INTERRUPTS.**—Interrupts in the computer system cause main program intervention, which causes the program to jump to the INTERRUPT ENTRANCE REGISTER. During an interrupt, an instruction, designated by the condition causing the interrupt, is executed.

An external interrupt results from an external device placing a signal on an external interrupt line. Appropriate action is generally taken by the interrupt program. Internal input/output interrupts are generated by the input/output section of the computer whenever a buffer, which has been initiated with a monitor imposed, terminates. Other conditions also cause internal interrupts, which are discussed in the following paragraphs.

A synchronizing interrupt (not associated with any input or output channel) is provided on the computer through a single line. Whenever certain events occur at some external device, which requests the computer to perform a given routine, this synchronizing input is used to alert the computer. When this occurs, control is transferred to the instructions located in control memory address 00016 (synchronizing interrupt entrance register).

Conventionally, all interrupt entrance locations are filled with one of two types of instructions:

- To ignore the interrupt, a set interrupt lockout instruction is used and the program will continue with the normal execution of instructions since the program address register (P-register) is not affected by the interrupt itself.

- A response to the interrupt requires a return jump (usually an indirect return jump) to the interrupt routine. The return jump instruction, under interrupt mode, saves the address of the next instruction that would have been executed in the normal sequence if no interrupt had occurred, rather than (as normally would be) the address of the return jump instruction + 1. This provides a return to procedures of the program as it was before being interrupted.

A real-time clock incrementing register is assigned address 00015 in control memory. It is used for timing three specific internal interrupting capabilities that are provided by hardware design and for any other program controlled timing activities.

An internal real-time clock increments the contents of address 00015 at a rate of 1,024 increments per second. The computer is capable of accepting real-time interrupts at frequencies up to 20 kHz. The real-time clock enable is controlled by a front panel switch of the computer.

When the real-time clock incrementing register overflows (777777 to 000000), the computer program is interrupted and the next instruction is taken from the real-time clock overflow interrupt entrance register (address 00013 in control memory). This interrupt may be locked out with the RTC disconnect.

The real-time clock monitor interrupt may be initiated by storing a desired time count in the real-time clock monitor word register (address 00014 in control memory) and enabling the real-time clock monitor through the *enable real-time clock monitor* instruction. When the RTC incrementing register equals the count stored in address 00014, the computer program is interrupted. The next instruction is taken from the RTC monitor interrupt entrance register (address 00012 in control memory). After this, the RTC monitor is disabled.

The intercomputer time-out interrupt is available during intercomputer operation. Any single bit of the RTC incrementing register may be wired to monitor the *resume* circuitry. (The *resume* circuitry provides the input acknowledge signal generated by a receiving computer upon completion of sampling input information lines.) When the real-time count reaches the specified bit, a designator is set. If no resume is received by the computer before the next time the count reaches that bit, the intercomputer time out interrupt is activated, and the next program instruction is taken from the resume fault (intercomputer) interrupt entrance register (control memory address 00011).

If an illegal function code is executed, a special case of an internal interrupt is generated. This fault interrupt causes the next instruction to be executed from address 00000 (fault interrupt entrance register).

**CONSOLE CONTROL.**—The console control area contains the controls, indicators, and logic circuitry required by an operator for program control. The switches and indicators used for other functions are not included in this section. Switches in the console control area are provided for master clearing of the computer, starting and stopping operations, operational mode selection, and controlling programmed stops and skips.

The start-stop logic consists of the logic necessary to start, stop, and master clear the computer, and to control the application of phase pulses for the several modes of operation. This logic is dependent upon the switch settings of control panel number 1 (drawer A2), control panel number 2 (drawer A4), and various programmed stops.

The mode selection logic determines the individual mode of operation to be performed by the computer. The four modes are load, phase step, operation step, and run. The modes of operation are selected by a switch on control panel number 1.

The program skip logic functions during the execution of several skip instructions to effect the skip procedure of the instruction if the necessary conditions have been met. A programmed skip is an instruction that allows the computer to omit the next sequential instruction, providing the conditions exist indicated by the skip instruction.

The program stop logic detects programmed stops and compares these instructions with the switch settings, which effect the stops. A programmed stop is an instruction that causes the computer to cease operation until manual intervention again returns it to a *run* status. There are five switch-controlled stops and one unconditional stop.

**PROGRAM TRANSLATION AND CONTROL.**—Each of the program instructions contains a coded command for specific computer sequencing. These commands must be decoded to perform the specific function indicated by the instruction. The program translation and control circuitry, consisting of five logically definable areas, interprets the coded command, establishes the sequence of events to be performed, and supplies the command enables for the operation. The five areas of the circuitry are the F register, function-code translator, format II translator, sequencer, and command enable circuit (fig. 3-6).

The F register is a 7-bit, flip-flop register that stores the function code during execution of an instruction. Two formats are used in designating an instruction—format I and format II. During a format I instruction, bits $2^0$ through $2^5$ contain the function code and bit $2^6$ remains cleared. If the programmed instruction is a format II instruction, bit $2^6$ is set and the minor function code is contained in bits $2^0$ through $2^5$. The function code will remain in the F register during the entire performance of the instruction.

The function code translator translates the function code contained in the F register into enable signals to initiate the necessary computer operation. Format I instructions are identified by a 2-digit octal code (00 through 47 and 51 through 77).

The format II translator supplies the necessary enables to alter the normal sequence of events to perform specific instructions. Format II instructions are identified by a 4-digit octal code (50 00 through 50 77). The octal 50 of an instruction sets the $2^6$ bit of the F register, and thus identifies the instruction as format II.

The sequencer influences the main timing sequence to ensure the proper execution of each instruction. To perform this function, the sequencer selects individual major command sequences in the proper order to execute the instruction. By selectively gating the main timing chain enables, only the operations of the selected command sequence are performed.

Major command sequences, available for selection by the sequencer, are divided into three general categories—control, input/output, and wait. Not all major command sequences are required to perform an instruction. It is the function of the sequencer to select those that fulfill the requirements of the instruction. In several instructions, only one sequence is required; others require several sequence combinations.

In addition to the major command sequences, two minor command sequences are initiated by the main timing chain under the influence of the appropriate major sequence. These sequences are the advance program sequence and the multiply/divide/shift sequence. These sequences operate independently from the major sequence enables.

The command enable circuitry provides the required enabling signals for transfer, shifting, scaling, and storage of words, instructions, or operands in, or between, the several registers within the computer functional logic. Command enables are generated by sequencer outputs or by individual instructions themselves, depending upon the operation to be performed.

**REGISTERS (CONTROL).**—The control section of the computer contains several registers used for the performance of control functions. These are the index registers, ICR register, SR register, P register, two S registers, and K register. Each register has a specific logic function to perform during the manipulation of instructions and commands.

The index registers are eight memory locations, the contents of which may be used to modify either the address or operand in certain specified odd-numbered instructions. Only one of the eight registers may be used during a given operation, and selection of the active index register is determined by the contents of the index control register.

The index control register (ICR) contains the programmed address of the currently active index register to be used for instruction modification. Any one of the eight index registers may be selected by the numerical value entered into the ICR register through program control.

The 5-bit SR register (special register), when active, is used to supply the four most significant bits of memory address in the S register. The maximum bit content of a programmed address is 12 bits. The memory address consists of 16 bits. The additional 4 bits are supplied by either the SR register or P register. When the SR register bit $2^3$ contains a 1, the SR register is considered active and supplies the necessary 4 bits. These 4 bits extend the u position of the programmed address to the required 16 bits. (The u position defines the low order 12 bits contained in format I instruction words.)

The P register (program address register) is used to store the address of the instruction currently being entered for execution. The contents of the P register are incremented by one when an instruction is transferred from its memory location, and thus contains the next sequential address to be entered. The 4 most significant bits of the address are supplied by the P register to the S register during those instructions when the SR register is not active.

The S registers (memory address registers) receive the address of a memory location at the start of a memory cycle and retain this address throughout the read/write cycle to control the translation circuitry. The S registers may receive the address from the input/output section (which generates certain assigned addresses), from control or arithmetic section, or from an input/output channel connected to a peripheral device capable of specifying an address. The S1 register is a 16-bit register associated with main memory. The 8-bit SO register is associated with control memory.

The K register is basically a 6-bit, double-rank counter used for both storage and control. Its primary use is to store and record shift and scale factor counts during execution of multiply, divide, shift, and scale factor instructions. It is also used to store selective skip and stop instructions. During operation, a transfer of bits from the upper rank to the lower rank decrements the contents by one. The return transfer from lower rank to upper rank prepares the register for the next sequence.

**SPECIAL CIRCUITS.**—Included in the control section are several circuits that perform unique functions in operation of the computer. These special circuits are parity, B register, and + 1 network, compare, overflow, and stop/skip circuits.

The parity circuits complete operation of the parity check, which is originated by the arithmetic section of the computer. The parity of the contents of the X register is checked in a pair-compare scheme to ensure an odd parity content. If the resulting signal indicates an even parity, parity flip-flop is set to notify associated computer logic of the parity status.

The B register and the ± 1 network are used to increment or decrement contents of a memory address during input and output operations. Also, they are used to update the currently active index register during either B skip or B jump instructions.

The compare circuitry is used in conjunction with the various jump commands. It determines certain conditions in the computer and furnishes enables for corresponding jump instructions.

The overflow circuit performs a test to determine whether an overflow condition exists during an arithmetic operation and notifies computer control logic of results.

The stop/skip logic is used to test for various conditions under which a stop or skip instruction is performed. Used with STOP and SKIP switches on Control Panel Number 2, the stop/skip logic compares the instruction to determine if this operation should be performed.

### Arithmetic Section

The arithmetic section of the computer (fig. 3-6) is composed of five flip-flop registers, a subtractive-type adder, and a logic-selecting circuit. The arithmetic section performs the following arithmetic operations: add, subtract, multiply, divide, shift, and scale factor. It also performs certain logical functions including masking, selective substitution, comparison, complement, and word transfers between elements of the arithmetic section, and between the arithmetic section, the control section, and memory. These operations and logic functions are initiated and sequentially executed by command enables supplied from the control section.

The five flip-flop registers are the AU register, AL register, X register, W register, and D register. The logic control circuit is the arithmetic selector. The subtractive-type adder is the modifying circuit, which produces the arithmetic results used for numerical computations.

**ARITHMETIC SELECTOR.**—The arithmetic selector acts as a distribution point for data entering and leaving the arithmetic section, with the exception of data concerning the P, S, and $Z_1$ registers. The selector receives data from the control section and A register; it sends data to the X and D registers, control (parity), and memory (store selector) sections.

**ADDER.**—The adder is an 18-bit, subtractive-type device. It provides, as an output, the solution of the quantity held in the X register minus the complement of the quantity held in the D register. In a subtraction problem, it is sometimes necessary to borrow from a higher order digit; this is also true in the adder. To increase the speed of operation, the adder is divided into three 6-bit sections. Each section is subdivided into two 3-bit subsections. A borrow request originating in any of the sections is passed across stages that cannot satisfy a borrow request to a stage that can satisfy the borrow request. Thus, time needed to propagate a borrow through 18 stages of the adder is reduced significantly.

**REGISTERS (ARITHMETIC).**—All registers in the arithmetic section are 18-bit, flip-flop registers. They are controlled by command enables from the control section. Brief descriptions of their capabilities are as follows:

A register. The A register is a 36-bit arithmetic accumulator that contains the product of two 18-bit quantities and contains the 36-bit dividend for a divide instruction. It is used as an accumulator for double-length arithmetic and logical function, and it has shifting and complementing capabilities.

AU register. This register is the upper accumulator (most significant 18 bits) of A, which contains a mask for logical instructions. It captures the remainder for the divide process, has shifting capabilities, and has complementing capabilities.

AL register. This register is the lower accumulator (least significant 18 bits) of A, which is used as the main accumulator of the arithmetic section for all functions. It contains the quotient for the divide process, contains sum for add to AL, and has shifting capabilities.

X register. An 18-bit exchange or communication register in the arithmetic section receives operands for arithmetic and logical instructions.

D register. An 18-bit arithmetic exchange register holds an operand for the adder during arithmetic operation.

W register. An 18-bit shifting register.

### Memory Section

The memory section is divided into seven logically definable areas (fig. 3-6): memory control, address translators, memory cores, inhibit circuits, sense amplifiers, the $Z_m$ register and $Z_1$ register.

**MEMORY CONTROL.**—Main memory control provides timing and enable signals to regulate memory circuit operation. When an input signal initiates a memory cycle, control circuits normally provide signals to perform a read cycle and a write cycle.

**ADDRESS TRANSLATORS.**—Address translators decode the memory address stored in the S1 register and enable the appropriate X line and Y line to select the decoded address. Memory control signals pulse select X and Y lines through the address translator to read and write at the selected address.

**MEMORY CORES.**—Main memory cores provide actual storage for the program and data words. Cores are located on memory stacks. Each stack consists of 18 planes, with 4,096 cores per plane. Each plane stores a single bit of an 18-bit word. The 18 planes together form the stack and store 4,096 18-bit words.

One of 64 X lines and one of 64 Y lines is selected by address translators to select one of the 4,096 addresses on a stack. Address translators also select one of 4, 8, 12, or 16 stacks in the memory.

**INHIBIT CIRCUITS.**—Inhibit circuits are used to inhibit writing a one at the bit positions that are to store a zero. At write time, X and Y lines are pulsed to write a one at all 18-bit positions of the selected address. If a zero is to be stored at any bit position in this word, an inhibit pulse must be generated for those positions.

**SENSE AMPLIFIERS.**—Sense amplifiers monitor 18 output lines from each stack (one line for each bit of a word). When cores for a single word are pulsed at read time, the sense amplifiers detect the one (core switches) and zero (core does not switch) outputs and stores them in the $Z_m$ register.

**REGISTERS (MEMORY).**—The $Z_m$ register provides necessary storage for the information read from main memory. Each of the four stacks containing 16,384 words in main memory has one $Z_m$ register; however, only one is used at a time. Thus, the $Z_m$ register is referenced singularly. The $Z_1$ register is used as a buffer for words being transferred between main memory and other sections of the computer.

### Input/Output Section

The input/output section of the computer (fig. 3-6) controls communications between the computer and connected peripheral devices. The input/output operations consist of three major functions: data transfers, interrupts, and special operation. During data transfer, one input/output operation transfers a single word between the computer and a peripheral device. A complete data transfer operation may consist of a number of input/output operations, which transfers a number of data words. Data transfer between the computer and two or more devices can be performed at the same time; individual input/output operations transferring words to the different devices are interlaced, or multiplexed. Interrupts provide the means for intervening in the main program; thus, giving the computer real-time fault-detection and correction capabilities.

Communication with the computer is carried on in an 18-bit parallel mode. The computer is provided with up to 16 input and 16 output channels, each logically independent of the others and brought to its own cable connector (32 connectors in all). Each channel contains 18 information lines plus control signals. If it is desired to communicate with an external device requiring more than 18 bits of parallel data, a dual channel option may be selected by one of four (eight for 16-channel computer) switches on the computer control panels. The selected option logically combines a pair of sequentially numbered even and odd channels to form a single channel having 36 bits of parallel data plus one set of control lines.

All signals on information lines and control lines are at two dc levels, which may be changed upon interchange of information. These may be held stable for microseconds or days, depending on the nature of the particular task.

Information is transferred in parallel to external devices on a *request-acknowledge* basis (recall chapter 6, "Data Transmission," *Fire Controlman 3*, NAVEDTRA 10276). The computer program initiates the process by scanning for a request using the scan sequence. The request is detected by the computer (which indicates the device is ready to perform). An external function command is transferred through the output information lines on the output cable, and the device performs the desired function. The computer-generated acknowledge will disable the request line (input request line for an input activity and output request for an output activity).

The computer responds to the input/output request at its convenience by storing the information presented on the input cable (if input) and answering with an input acknowledge on the same cable. Or, if output, the computer transfers a word from storage to the output cable and answers with an output acknowledge on that cable.

Commands may be a single word command or a multiword command, depending on the requirements of the external device. If multiword commands are required, the device presents an output request to the computer upon accepting the first word. The computer responds at its convenience and transfers each succeeding command word in a buffer mode. The external function line is set each time a command word is placed on the output lines. In another method, the computer can *force* command words to external devices; in which case, the output request line need not be set. As soon as the output register is available, the computer transfers the word to the device.

**INPUT/OUTPUT PRIORITY.**—The computer performs an input/output priority scan concurrently with a program instruction sequence. Input/output priority scan sequentially scans priority A events listed in table 3-2. If no

**Table 3-2.—Sequence Scan Priority A**

| PRIORITY A | SCAN FOR DATA EVENTS |
|---|---|
| 1 | Real-Time Clock Update |
| 2 | External Interrupt |
| 3 | External Function Request |
| 4*, 5* | Output Request of External Function |
| 5*, 4* | Input Data Request |

*Each time either 4 or 5 is detected, they shall reverse their priority rating.

180.82

priority A event is detected, the scan sequentially scans the priority B events listed in table 3-3.

The priority A events 2, 3, and 4 are channel dependent and are scanned for each channel, starting with the highest numbered channel and ending with channel 0. (A priority 4 event on channel 15 has a higher priority than a priority 2 or 3 event on channel 14.) If one or more priority A events on one channel are detected, the highest priority event is processed, and the scan is restarted at the beginning of the priority A scan.

Priority B events 6, 7, and 8 are channel dependent and are scanned for each channel starting with the highest numbered channel and ending with 0. If one or more priority B events are detected, the highest priority event is processed and scan is restarted at the beginning of priority A scan. If no priority B event is detected, scan is restarted at the beginning of priority A scan.

**Table 3-3.—Sequence Scan Priority B**

| PRIORITY B | SCAN FOR INTERRUPT EVENTS |
|---|---|
| 1 | Fault (Program) |
| 2 | Resume Fault |
| 3 | Real-Time Clock (monitor) |
| 4 | Real-Time Clock (Overflow) |
| 5 | Synchronizing Interrupt |
| 6 | External Interrupt (Monitor) |
| 7 | External Function (Monitor) |
| 8 | Output (Monitor) |
| 9 | Input (Monitor) |

180.83

**INPUT/OUTPUT SEQUENCE OF EVENTS.**—Scan time (to search for an input/output request) is concurrent with instruction time if channels are not busy and concurrent with word transfer time if channels are busy. The sequence of events (input/output request) are as follows:

| Order of Input/Output Sequence | Event Executed |
|---|---|
| 1. | Read current address word from control-memory location specified by channel from input/output translator or externally specified index. |
| 2. | Read terminal address word from control memory next sequential address. Compare with current address word. Begin scanning for new request. |
| 3. | Modify and restore current address word to control memory. |
| 4. | Transfer data or function word (single or dual channel). If an externally specified index, input from an even channel, output takes place on both. |
| 5. | Transfer second data or function word if dual channel operation. Even channel equals the most significant 18 bits. |
| 6. | Complete the sequence of the instruction that was in process when the input/output request was detected or handle new input/output request. |

The external interrupt (EI) from an external device may be considered as a request. It requests the computer to accept an 18-bit status word on the input data lines and store it in memory (address 101 + 2K, K = channel number). Accepting the EI signal sets the EI monitor interrupt signal, which is handled as a separate request for input/output services.

If no input/output requests are detected during the first half of scan (scan A), the computer checks for special and monitor interrupt signals during the second half (scan B). This interrupts the normal sequence of instructions and transfers control to a special interrupt entrance address. After an interrupt is honored, the interrupt lockout must be program cleared to honor another interrupt. This flip-flop, as well as the external lockout flip-flop, can be program set and cleared to allow control of interrupts. Also, the program can cause itself to wait for an interrupt.

**CONTROL SIGNALS.**—Control signal exchanged between the computer and peripheral equipment are synchronized to ensure that the control line has been returned to a one state between successive recognitions of control signals. This requirement guarantees that only a single recognition pulse will be generated each time the control signal is set to a one state, and it also is a safeguard against false gating of data lines caused by noise or other spurious signals appearing on the control lines. There is no such restriction on the information lines. These need not be cleared to zeros between successive words.

The input acknowledge is the computer response to an input request or to an interrupt. To eliminate misinterpretation of the input acknowledge signal, peripheral equipment must not interrupt until its last input request has been acknowledged by the computer. A request signal (or an interrupt), once set, must remain set until it is acknowledged. This is necessary to maintain synchronism in the passing of data words back and forth between units. Under emergency conditions, when data loss is of secondary importance, the input request may be dropped, but data lines must remain stable for not less than 4 microseconds. If during this 4-microsecond interval an input acknowledge is received, the peripheral equipment may assume successful transfer of the last data word. At any time, after the 4-microsecond interval, the peripheral equipment may change the data lines and send an interrupt.

The output acknowledge or external function acknowledge signal is the computer response to an output request or external function request. Data or command codes are placed on the information lines and identified by the output acknowledge or external function respectively.

The override instruction to an intercomputer channel is not executed until a resume (acknowledge) is received from the receiving computer (until the resume flip-flop is set) or by a set resume instruction in the program which would have to precede the override. Therefore, any delay in an acknowledge from the receiving computer holds up the program, since the program will not proceed until the override instruction has been executed, which does not occur until the resume flip-flop has been set.

Information lines must be stable at the time they are gated into the storage elements. This self-evident axiom dictates the timing relationships between the information lines and the control signals. In the case of computer output, this rule requires the computer to provide a suitable delay between gating information into output registers and raising the output acknowledge or the external function signals, and similarly requires the computer to drop the output acknowledge or the external function a suitable interval before changing the information on the lines. Thus, the peripheral equipment is guaranteed that output lines are stable for sampling any time the output acknowledge or external function is present. In the case of input, the computer detects the input request or the interrupt before sampling the data lines. The peripheral equipment cannot change the information lines after raising either its input request or interrupt until an acknowledge has been received, indicating that the data lines have been sampled (except as stated above).

**SPECIAL MODES OF OPERATION.**—The input/output section operates in several special operational modes. These include dual channel operation, externally specified indexing (ESI), externally specified addressing (ESA), continuous data mode (CDM), and intercomputer communication mode.

**Dual Channel Operation.**—As previously mentioned, users of the computer have the option of communicating over the 18-bit parallel single channels or of logically combining sequentially even and odd numbered channels into a 36-bit parallel dual channel (dual channel operation). This option is selected by one of eight switches on the control panels. Selection of this dual channel option effects only that pair of channels selected, but both input and output channels of a given channel number are combined by a single switch setting. For example, if the first switch is activated, input and output channels 0 and 1 are combined to form a 36-bit input and a 36-bit output channel, but input and output channels 2 through 15 remain 18-bit logically independent channels. If this dual option is selected, the set of control lines belonging to the odd-numbered channel have control of the information transfers over all 36 lines.

With this dual option selected, energizing the request lines or the interrupt line on the even-numbered channel causes the computer to interpret this as a desire to communicate in single-channel mode, and the computer replies over the even-numbered set of control lines. Eighteen bits of information are accepted from the peripheral equipment on the even-numbered set of lines, and as in any single channel operation, identical information appears to both sets of output lines.

**Externally Specified Index (ESI).**—The externally specified index feature provides peripheral devices with means of specifying core storage areas in the computer's memory for any input or output transfers they may request. The ESI mode of operation is useful as a multiplexing device for a number of slow transfer peripheral units occupying one dual channel. The buffer control words governing the transfers are located at the index address. If input is desired, an input request is presented with the index on one channel of the pair and the data on the other channel. If output is desired, an output request is presented with the index address.

Externally specified indexing is useable only in a dual-channel mode. The corresponding ESI switch (one of eight, for each pair of channels) must also be selected on the computer control panel. The index address word is always placed on the set of input lines for the odd-numbered channel. If the peripheral equipment desires to send an input word, it will place the input data on the 18 lines of the even channel and raise the odd input request line. The computer replies on the odd input acknowledge line. If the peripheral equipment should raise the even input request line instead of the odd, the computer interprets this as normal single channel communication and ignores the index address. The computer program must provide an active channel for the ESI operation.

If the peripheral equipment wants a word of output data, it places the index address on the odd-numbered set of input lines and raises the odd output request. The computer replies with 18 bits of data, duplicated on both sets of output lines, with the odd channel output acknowledge. Activation of the even-numbered output request similarly causes the computer to ignore the ESI feature.

A sequence of events for output from a computer using ESI is as follows:

1. The computer program provides an active output channel to the equipment.
2. The external device places an even-numbered 16-bit control memory index address, n, on the odd input channel.
3. The external device sets the output request control line on the odd output channel.
4. The computer detects the output request, and at its convenience, reads and compares the addresses stored in n and n + 1.
5. The computer transfers the word from the address located in n + 1 to both output channels.
6. The computer sets the output acknowledge on the odd channel.

The sequence of events for input is the same as for the output except that a data word is placed on the even input channel with the index address on the odd channel, and an input request is raised. The data word is stored at the absolute address stored in n + 1. The computer responds with an input acknowledge.

Addresses n and n + 1 are treated as normal buffer control words with the same buffer control options available. When the monitor interrupt occurs during the ESI input/output sequence, the index address, n, is stored in the associated monitor interrupt status word location, and the channel is deactivated.

**Externally Specified Addressing (ESA).**—The externally specified addressing (ESA) feature provides peripheral devices with a means of specifying an absolute core memory location for storage or retrieval of data. An active dual-channel mode of operation is required for computer response to this function. The address is presented on one channel and the data transmission on the other. If input is desired, the external device presents an input request with the address and data. If output is desired, an output request is presented with the address.

Externally specified addressing is a switch selectable dual-channel mode of operation that allows external devices random access to core memory for retrieval and storage of data as opposed to the contiguous addressing scheme associated with normal buffers. Individual and/or random entries in a data pool lend themselves to an effective use of ESA. The external unit must be capable of presenting the absolute address on the odd input channel of the pair.

The sequence of events for output from the computer using ESA is as follows:

1. The computer program provides an active output channel to the equipment.
2. The external device places a 16-bit absolute address, n, on the odd channel input lines.
3. The external device sets the output request control line on the odd output channel.
4. The computer detects the output request, and at its convenience, transfers the address, n, to the S register.
5. The computer places the contents of address, n, on both output channels of the pair.
6. The computer sets the output acknowledge on the odd channel.

The sequence of events for input is similar to output except that a data word is placed on the even input channel with the storage address on the odd channel and the input request line is raised. The computer responds with an input acknowledge.

**Continuous Data Mode (CDM).**—The continuous data mode, requested when initiating a buffer on a channel, is a feature that provides an automatic reinitiation of the buffer upon termination. A new pair of buffer control words is transferred to the control-memory buffer-control addresses from the control memory CDM addresses for that channel. The monitor interrupt can be incorporated with the CDM, and, if so, the interrupt occurs each time the buffer is terminated and reinitiated. The CDM is especially useful when a continuous, high rate, stream of data must be transferred in or out of the computer.

Assume a buffer has been initiated by an appropriate instruction such as *initiate input on channel 3*. Further assume that the input transfer has been completed.

If the CDM bit is set (bit 17 of the terminal address buffer control word), the contents of control memory addresses $26_8$ and $27_8$ are transferred to addresses $66_8$ and $67_8$, and the input buffer for channel 3 is reinitiated without program attention. Before the buffer (defined by the buffer control words [BCWs]) is completed, the program has the option of storing another set of BCWs in addresses $26_8$ and $27_8$ with or without the CDM bit set. If set, this cycle continues until the program clears the CDM bit in address $26_8$. Similar action occurs for output and external function buffers.

**Intercomputer Communication Mode.**—Eight switches on the computer control panel provide the option of intercomputer communication (intercomputer communication mode) to any or all input/output channels. The selection of a given input/output channel as an intercomputer channel has no effect upon the modes of the unselected channels. An intercomputer channel can function in either the dual or ESI mode in addition to the normal 18-bit mode.

The selection of a given channel as an intercomputer channel affects only the logic concerned with the output and external function buffers. A channel that is sending data or external function messages to a given peripheral device holds the data in the output registers for a fixed minimum time period, after which an output or external function request on any other channel that is part of this 4-channel group can cause the data to be changed. However, a channel sending data or external function messages to another computer must hold the information in the output register(s) until the receiving computer acknowledges receipt of those words.

This acknowledge signal is received on what is known as the output request line when not in intercomputer mode. This line, in the intercomputer mode, is known as the resume line. In the case of Computer Mk 152 to Computer Mk 152 communication (fig. 3-8), this resume line is connected to the input acknowledge line of the receiving computer. Activation of the resume signal on the transmitting computer channel causes the setting of the resume flip-flop for that even or odd group of four channels. It is this flip-flop that, when set, allows the transmitting computer to proceed to the next highest priority output function (the next output data word of external function message).

If an output channel is holding data for another computer, the output registers will be tied up until the intercomputer time-out interrupt branches to a remedial routine. During the interim, no output buffers or external function buffers to other equipment on that channel group can proceed. To limit the possibility of hang-up occurring, two instructions and the intercomputer time-out interrupt are provided so the computer program can monitor the status of the resume flip-flop. These instructions are (1) *Skip On No Resume* and (2) *Set Resume*. The first allows examination of the resume flip-flop. The second allows the program to correct the situation in which the hang-up exists.

## DIGITAL COMPUTER SET AN/UYK-7(V)

The AN/UYK-7(V) computer was developed to fulfill the needs of the military for a modular computer configuration that is flexible enough to meet the requirements for small, medium, or large systems without sacrificing versatility.

The AN/UYK-7(V) features many next generation data processing characteristics. Rapid transfer and partial data processing are provided in communications between external devices and large internal random-access storage. The unique timing and access priority techniques used with the main core memory permit the operation of several parallel memories. This greatly increases the computer operating speed. The advanced timing features of this computer can produce an average command execution time as low as 1.5 microseconds. The single cabinet configuration of the AN/UYK-7(V) computer has an input transfer capability of over one million 32-bit words per second.

In this section, we will discuss the general characteristics, instruction format, and theory of

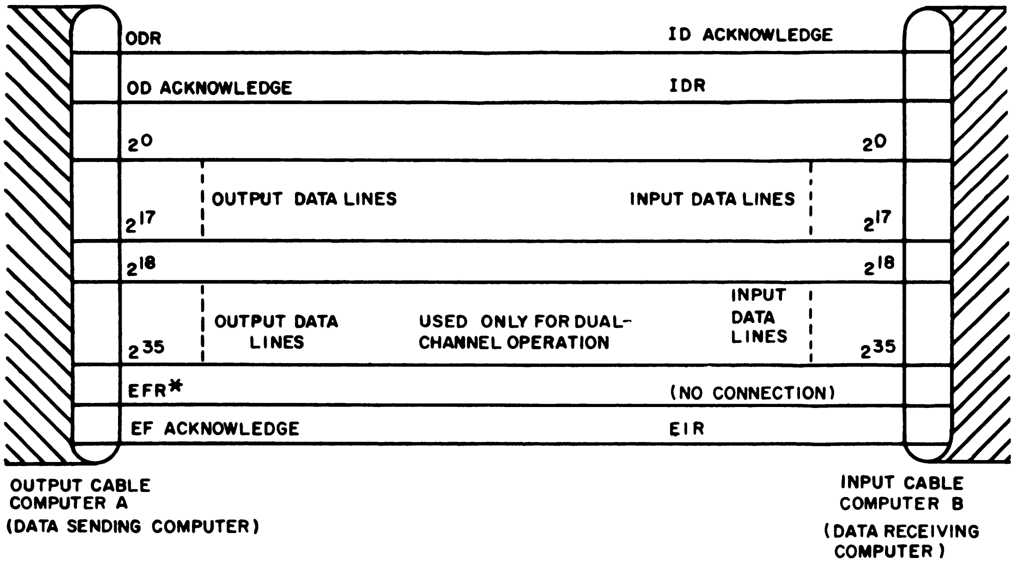

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Figure 3-8.—Computer-to-computer communication.

a single-cabinet AN/UYK-7(V) computer set. Both core memories and double density mated film memories (DDMFM) are discussed. Data transfer, internal to the computer set, are discussed using a simplified block diagram for each module of the computer and a simplified block diagram of the entire computer set.

## PHYSICAL DESCRIPTION

The AN/UYK-7(V) computer set is designed to operate either as a single processor or as a multiple-processor system. A single-cabinet, single-processor can be hardwired to contain 96K words of memory. In a normal single-cabinet single-processor, memory banks 0 and 1 are core memory, and it is possible to add a DDMFM module for bank 2, providing a total of 64K word memory without any wiring changes. The DDMFM can replace any core memory (without any hardware wiring changes) so long as it is the highest even-numbered bank. It can, through addressing, command additional memory units containing up to a maximum of sixteen 16K word modules (core memory) or eight 32K word modules (DDMFM).

An AN/UYK-7(V) single cabinet computer configuration consists of the following modules:

- One central processing unit (CPU)
- One input/output controller unit (IOC)
- One input/output adapter unit (IOA)
- Three main memory units (MMU)
- One power supply unit (PSU)
- One computer control unit (optional remote console)
- One maintenance panel

The basic single-cabinet configuration (fig. 3-9) is the primary building block around which all other configurations are built. Configurations can vary the basic single cabinet computer configuration by reducing the number of components (fewer memory units, DDMFM units, and I/O channels). The single-cabinet computer configuration can also be expanded (adding one or more cabinets in parallel to the basic computer) to include more memory units, more I/O channels, or another CPU.

The AN/UYK-7(V) computer has a multiprocessing capability that allows a number of CPUs to operate simultaneously in the same system. Communication between the CPU, MMUs, and IOC is by way of a bussed communication system consisting of three types of busses—instruction (I bus), operand (OP bus), and input/output memory (I/O MEM bus). As shown in figure 3-10, the CPU communicates with the MMUs, by way of both instruction (I) and operand (OP) data busses, and with the IOC by way of the operand (OP) bus. The IOC communicates with MMUs by means of an I/O MEM bus. The busses consist of connecting cables, connected in a daisy chain fashion, between the CPU, MMUs, and IOC. Interface timing between various units of the computer is handled on an asynchronous basis. Data transfers are performed through a request/acknowledge system.

The computer contains three types of memory—main memory, control memory, and nondestructive read-out (NDRO) memory. *Main memory* is a destructive read-out (DRO) memory consisting of three 16,384-word core units or three 32,768-word DDMFM units. Maximum expansion capability for a computer with one CPU is sixteen core units or eight DDMFM units (262,144 words). The main memory stores all instructions and operands processed during normal programmed operation. The *control memory* consists of 82 flip-flop storage registers that hold up to 32 bits each. The control memory, located in the CPU, stores data used for operand address modification, interrupt execution, and monitor clock update operation. The *NDRO memory*, also located in the CPU, consists of 512 or 1,024 hardwired words. It is a predetermined set of programs designed as a permanent part of the CPU. The NDRO memory provides a means of automatically loading the DRO memory. It also provides a hardware fault analysis program and a load-failure analysis program. The NDRO memory is designed to meet the requirements of each individual site. The bootstrap program, designed to load DRO memory, is different from site to site because of the different types of peripheral equipment and input/output channels used.

### Operator Controls

Three sets of operator controls are available to control the computer set. Two of these,

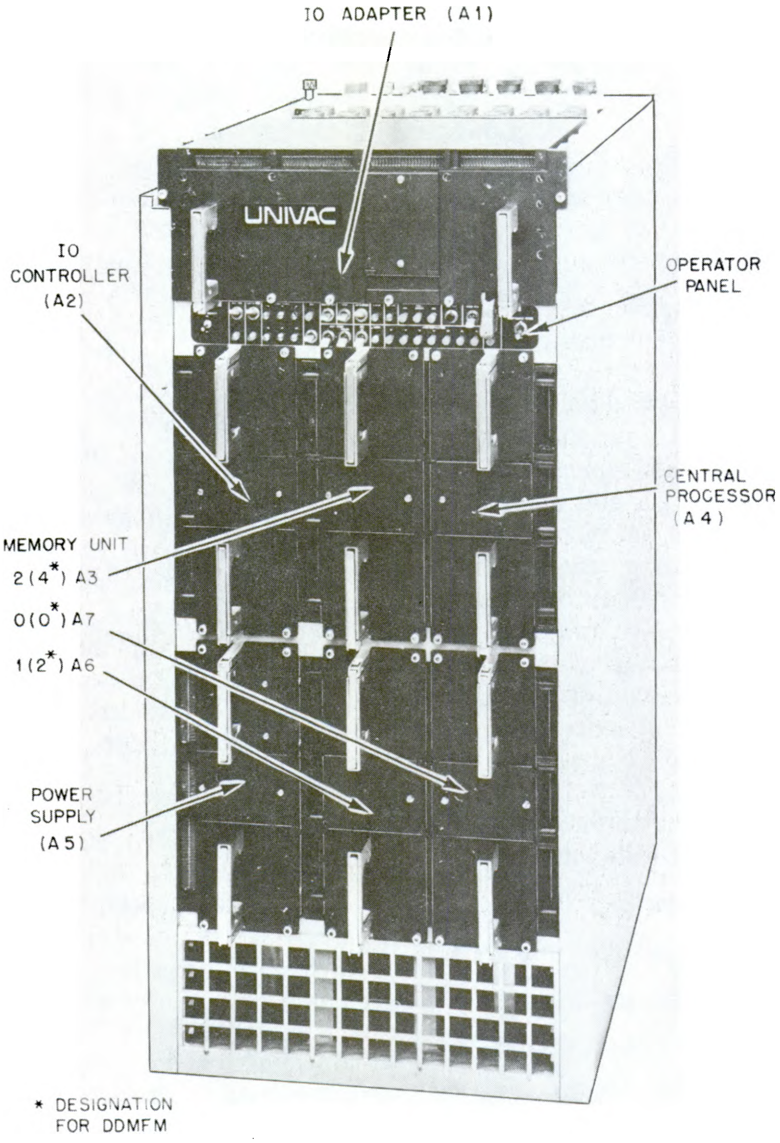

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Figure 3-9.—Computer Set AN/UYK-7(V), basic single-cabinet configuration, A.

the maintenance panel (fig. 3-9, view B) and the remote console (fig. 3-9, view C), are optional units. The third set of controls, the operator panel, is located on the front of the electrical equipment cabinet. Normal program operation can be initiated from any one of the three units, depending upon software configurations. A brief description of the function of each unit is contained in the following paragraphs.

**OPERATOR PANEL.**—The operator panel (fig. 3-9, view A), located on the front of the equipment cabinet, enables the operator to apply computer ac and dc power, start and stop computer operations, observe faults and

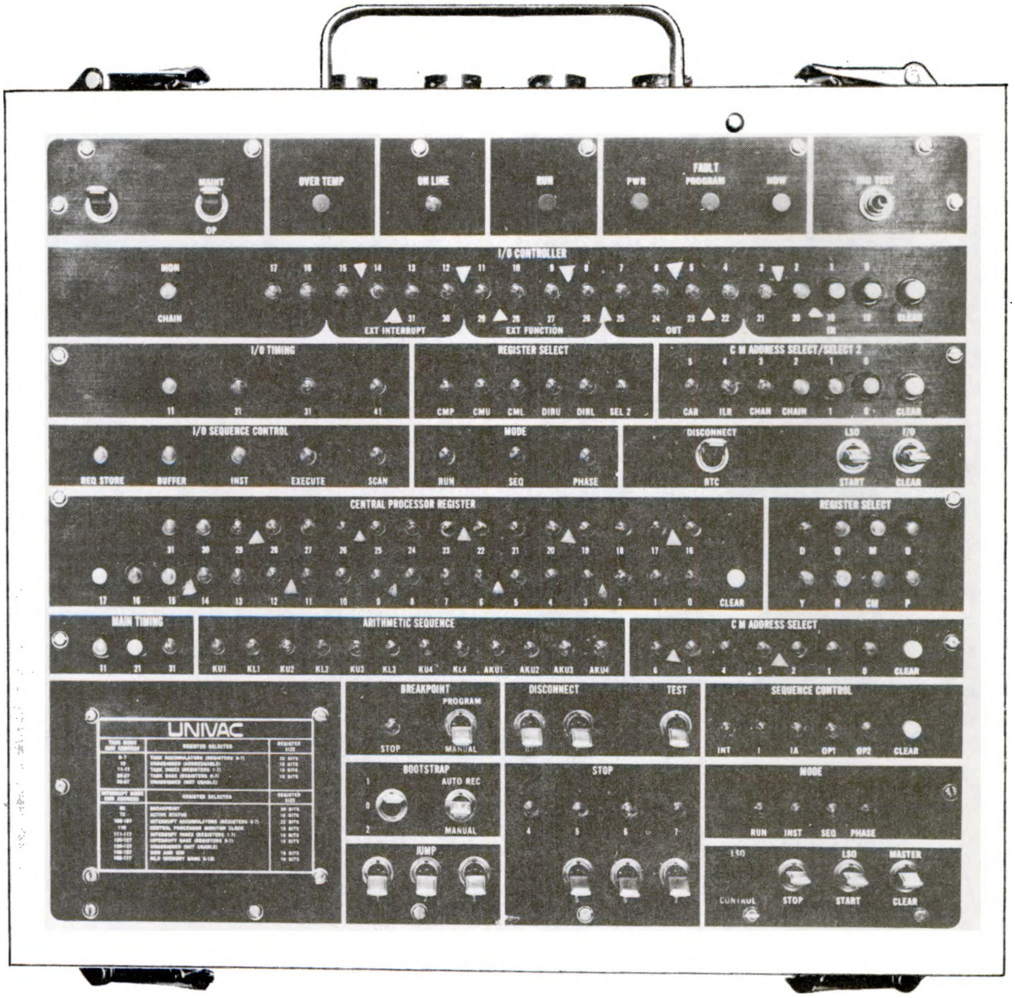

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Figure 3-9.—Computer Set AN/UYK-7(V), maintenance panel, B—Continued.

overtemperature conditions, apply dc power to the maintenance console, and test visual indicators/audible alarm capability.

**MAINTENANCE PANEL.**—The maintenance panel (fig. 3-9, view B) may be mounted in the brackets on the top of the computer cabinet, or located a maximum of 15 feet from the computer. The maintenance panel enables the technician to effectively operate the CPU and the IOC under expanded and varied conditions, and at various speeds and modes of operation. The primary function of the maintenance panel is to allow maintenance personnel to monitor instruction words and their operation, and to check the contents of the arithmetic and control registers. Registers and controls are monitored when preventive maintenance is performed, or when a computer malfunction occurs. When the maintenance panel MAINT/OP switch is in MAINT position and computer and maintenance panel power is applied from the operator's panel, the maintenance panel control overrides the operator panel control.

Some, but not all, of the functions that can be performed from the maintenance panel are as

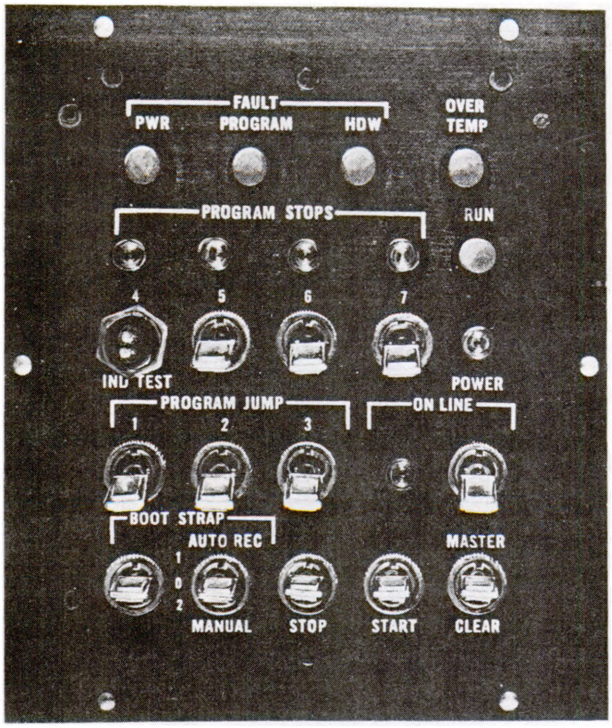

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**Figure 3-9.—Computer Set AN/UYK-7(V), and remote console C—Continued.**

follows: program initiation, CPU manual read, CPU manual write, IOC manual write, and repeated instruction execution. Detailed procedures for performing these and other operations are contained in the *Maintenance Manual for Computer Set AN/UYK-7(V)*, SE610-AW-MMA-010.

**REMOTE CONSOLE.**—The remote console (fig. 3-9, view C) enables an operator to control operation of the computer system from an area remotely located from the computer room. The remote console can be located up to a maximum of 300 feet from the computer. The remote console has basically the same capability as the operator panel except that power cannot be applied to the computer system from the remote console. The remote console ON-LINE switch can override control of the computer from either the operator panel or the maintenance panel when computer power has been applied from the operator panel.

## UNIT FUNCTIONAL DESCRIPTION

A simplified block diagram of the Computer Set AN/UYK-7(V) (fig. 3-11) will help you tie the

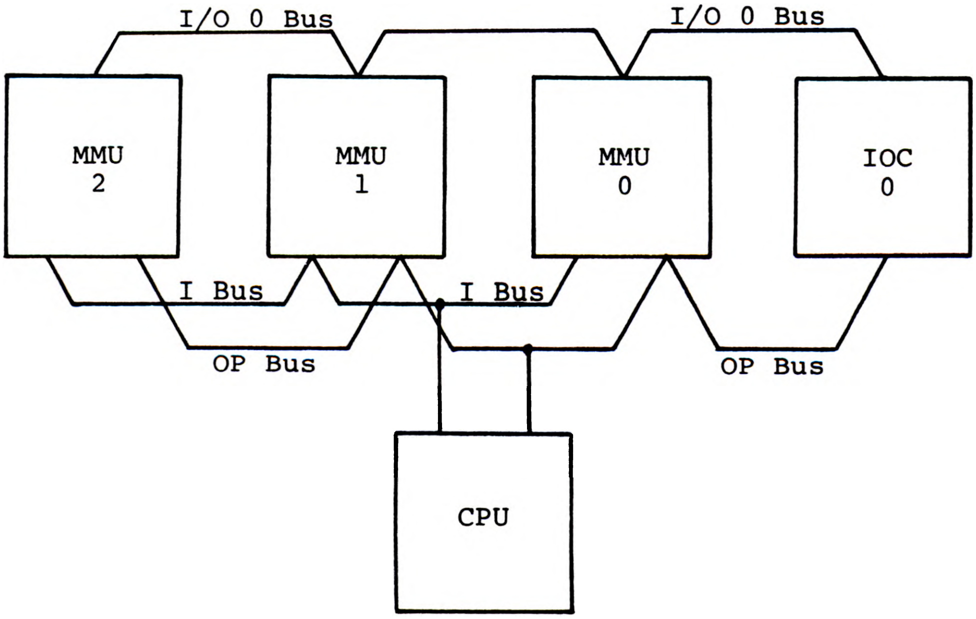
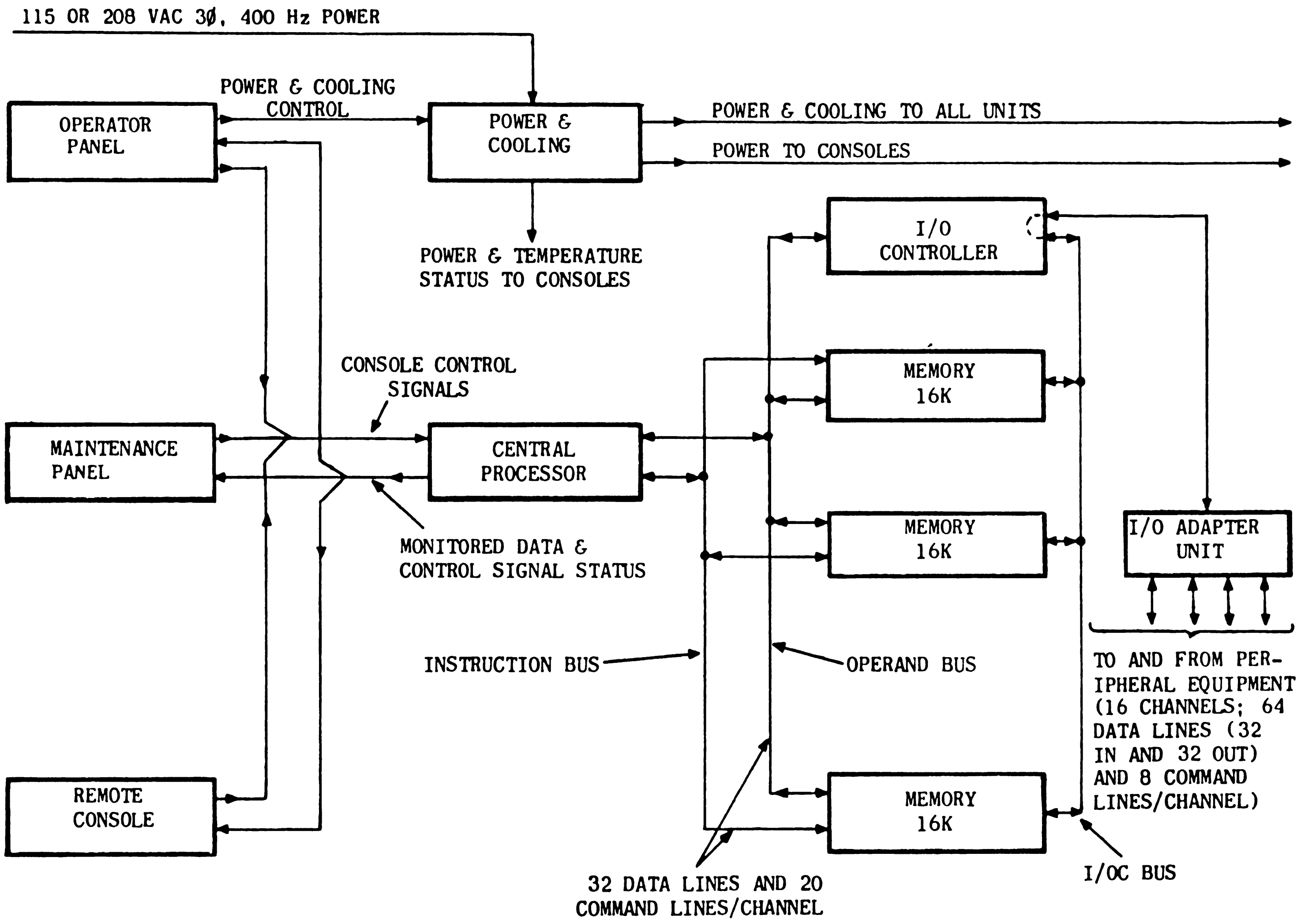


**Figure 3-10.—Central processor communications interconnection (single cabinet).**


115 OR 208 VAC 3∅, 400 Hz POWER
POWER & COOLING CONTROL
OPERATOR PANEL
POWER & COOLING
POWER & COOLING TO ALL UNITS
POWER TO CONSOLES
POWER & TEMPERATURE STATUS TO CONSOLES
I/O CONTROLLER
CONSOLE CONTROL SIGNALS
MEMORY 16K
MAINTENANCE PANEL
CENTRAL PROCESSOR
MEMORY 16K
I/O ADAPTER UNIT
MONITORED DATA & CONTROL SIGNAL STATUS
INSTRUCTION BUS
OPERAND BUS
TO AND FROM PERIPHERAL EQUIPMENT (16 CHANNELS; 64 DATA LINES (32 IN AND 32 OUT) AND 8 COMMAND LINES/CHANNEL)
REMOTE CONSOLE
MEMORY 16K
I/OC BUS
32 DATA LINES AND 20 COMMAND LINES/CHANNEL

151.295

Figure 3-11.—Computer Set AN/UYK-7(V), simplified block diagram.

operator controls to the various functional units of the computer set. Console control signals are parallel between the remote console, operator panel, and the maintenance console. Monitored data (from various registers) are also paralleled between the remote console, operator panel, and maintenance panel. Not all of the data available to the maintenance panel is distributed to, or used by, the remote console and operator panel. As noted in the previous tables of controls and indicators, the remote console and operator panel cannot display all of the data that is displayed on the maintenance panel. Control signal status information is distributed to all three units (remote console, maintenance panel, and operator panel). Only the operator panel has power and cooling control. Power and cooling status signals are distributed to all console/panels by the power and cooling function of the computer set.

Displayable information regarding program operation (register contents, or status) comes through either the CPU or IOC to the console/panels. Functional analysis of the IOC, IOA, and MMU is covered later in this chapter.

This section of the chapter is divided into six parts. The first part describes the function of the repertoire of instructions; the remaining five parts each describe the function and analyze the operation of a particular assembly: (1) central processing unit (CPU), (2) I/O controller (IOC), (3) I/O adapter (IOA), (4) core memory unit (CMU), and (5) double-density mated film memory (DDMFM). The power supply unit (PSU) (fig. 3-11) is not covered in this RTM. Detailed operations of the PSU are contained in the technical manual for the computer set. Throughout this section, simplified block diagrams are used to show major functional operations. For simplicity, abbreviated and combined forms of logic signals are used. For detailed timing and logic diagrams, refer to maintenance manuals SE610-AW-MMA-010, 020, 030, and 040, respectively.

### Instruction Format

Instruction words for the central processing unit (CPU) are arranged into five different formats; three are whole words of 32-bit lengths (formats I, II, and III), and two are half words of 16-bit length (formats IVA and IVB).

**FORMAT I.**—Format I instruction words consist of 32 bits arranged as shown in figure 3-12. The function code designator (f) defines the instruction the computer is to execute. The accumulator designator (a) normally selects one of eight accumulators within CPU control memory, whose contents are processed by the instruction. The operand interpretation designator (k) specifies whether the operand is to be read from or stored into memory in whole-word, half-word, or quarter-word form. For some instructions, the a and k designators are combined to form a single ak field. The indirect address designator (i) determines whether the instruction is to address an operand in direct or indirect form. (Indirect addressing will be covered later.)

The index (b) and base (s) designators specify the particular index and base registers whose contents are to be used to modify the basic operand

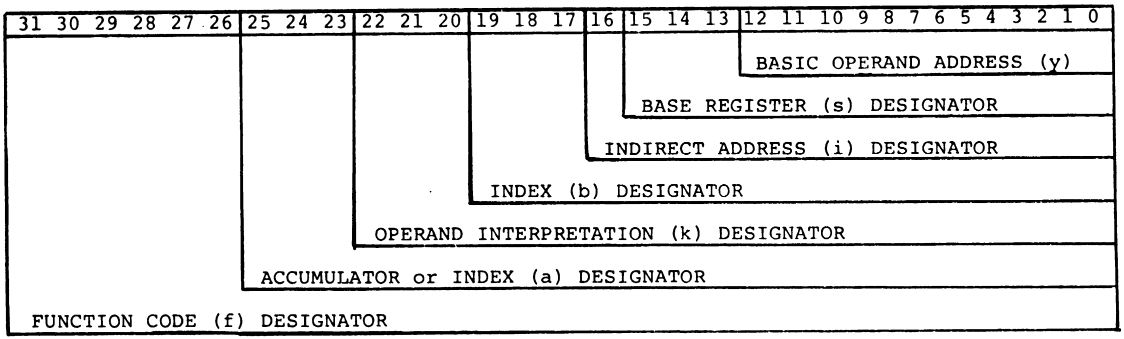

31 30 29 28 27 26
25 24 23
22 21 20
19 18 17
16
15 14 13
12 11 10 9 8 7 6 5 4 3 2 1 0
BASIC OPERAND ADDRESS (y)
BASE REGISTER (s) DESIGNATOR
INDIRECT ADDRESS (i) DESIGNATOR
INDEX (b) DESIGNATOR
OPERAND INTERPRETATION (k) DESIGNATOR
ACCUMULATOR or INDEX (a) DESIGNATOR
FUNCTION CODE (f) DESIGNATOR

Figure 3-12.—Format I instruction word.

address (y). This modification involves adding the contents of the selected index and base registers to the basic operand address to form a modified operand address. Modification of the basic operand address is necessary to allow the addressing of an operand in any one of the sixteen possible core memory units, or eight double density memory units.

**FORMAT II.**—Format II instruction words consist of 32 bits, arranged in a format shown in figure 3-13. Only whole word operands or double length operands are processed by format II instructions. The k designator is used to define a subfunction code (f2 designator). This f2 designator is used with the normal f designator to specify a function code of three octal digits, of which the most significant digit is always 0. The other format II instruction designators are interpreted in the same manner as format I instruction designators.

**FORMAT III.**—Format III instruction words consist of 32 bits, arranged in the format shown in figure 3-14. Format III instructions are jump instructions, and they are used only to process whole word operands. The k designator field is divided into two parts—a 2-bit subfunction code (f3) designator, and a single z designator bit that must be zero. All other designators are interpreted in the same manner as format I instructions.

**FORMAT IVA.**—Format IVA instructions consist of 16 bits arranged in the format shown

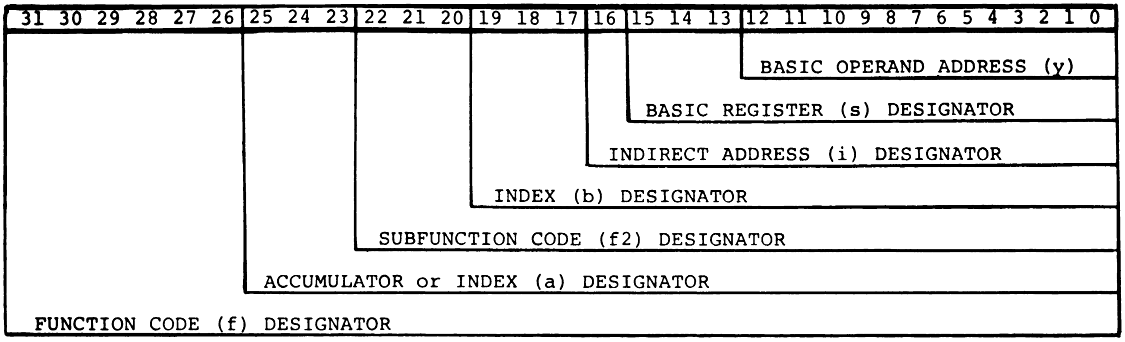

31 30 29 28 27 26
25 24 23
22 21 20
19 18 17
16
15 14 13
12 11 10 9 8 7 6 5 4 3 2 1 0
BASIC OPERAND ADDRESS (y)
BASIC REGISTER (s) DESIGNATOR
INDIRECT ADDRESS (i) DESIGNATOR
INDEX (b) DESIGNATOR
SUBFUNCTION CODE (f2) DESIGNATOR
ACCUMULATOR or INDEX (a) DESIGNATOR
FUNCTION CODE (f) DESIGNATOR

Figure 3-13.—Format II instruction word.

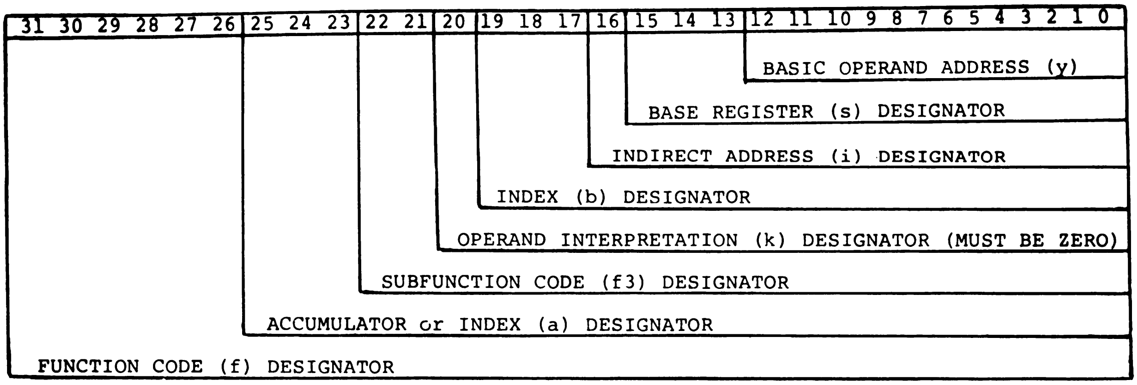

31 30 29 28 27 26
25 24 23
22 21
20
19 18 17
16
15 14 13
12 11 10 9 8 7 6 5 4 3 2 1 0
BASIC OPERAND ADDRESS (y)
BASE REGISTER (s) DESIGNATOR
INDIRECT ADDRESS (i) DESIGNATOR
INDEX (b) DESIGNATOR
OPERAND INTERPRETATION (k) DESIGNATOR (MUST BE ZERO)
SUBFUNCTION CODE (f3) DESIGNATOR
ACCUMULATOR or INDEX (a) DESIGNATOR
FUNCTION CODE (f) DESIGNATOR

Figure 3-14.—Format III instruction word.

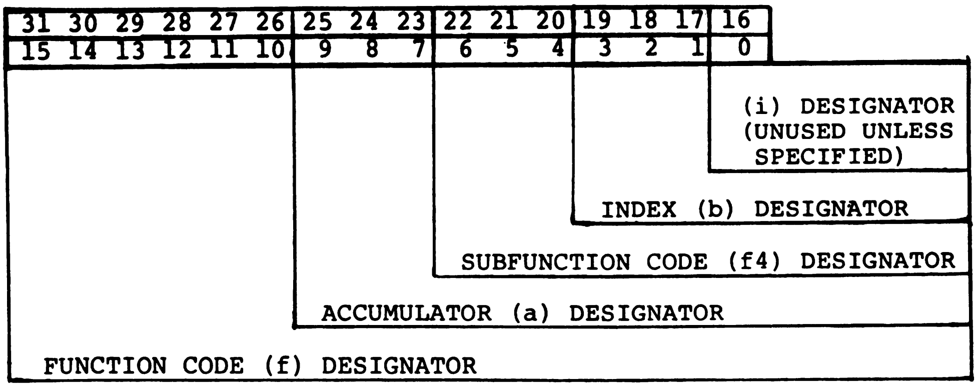

31 30 29 28 27 26
25 24 23
22 21 20
19 18 17
16
15 14 13 12 11 10
9 8 7
6 5 4
3 2 1
0
(i) DESIGNATOR (UNUSED UNLESS SPECIFIED)
INDEX (b) DESIGNATOR
SUBFUNCTION CODE (f4) DESIGNATOR
ACCUMULATOR (a) DESIGNATOR
FUNCTION CODE (f) DESIGNATOR

**Figure 3-15.—Format IVA instruction word.**

in figure 3-15. The format IVA instruction is used to perform operations not requiring an operand from main memory. The lower 16 bits, which are normally used for operand addressing, are not needed for format IVA because the operand to be manipulated is already resident in the CPU, due to a previously executed instruction. The accumulator (a) designator and/or the index (b) designator specifies one of eight accumulator and/or seven index registers, whose contents are processed with the instruction subfunction code (f4) designator. The i designator is used only when specified in a particular instruction.

**FORMAT IVB.**—Format IVB consists of 16 bits arranged in the format shown in figure 3-16. The format IVB instruction format is used to shift data stored in an accumulator. The accumulator (a) designator specifies one of eight accumulators in control memory. The shift count (m) designator specifies a shift count or a source of a shift count and is interpreted as follows:

1. If the upper two bits of the m designator equal 10, the shift count is contained in the B register specified by bits 3-1.

2. If the upper 2 bits of the m designator equal 11, the shift count is contained in the accumulator specified in bits 3-1.

3. If the upper 2 bits of the m designator equal 0X, the shift count is contained in the lower 6 bits of the m designator field. (Maximum shift permitted is 63 places.)

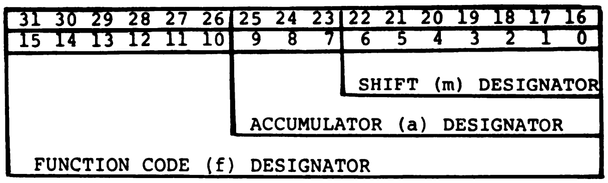


**Figure 3-16.—Format IVB instruction word.**

**DESIGNATORS.**—In this section we will discuss the normal interpretations of the various instruction designators that apply to most of the CPU instructions. Some instructions interpret these designators in a manner unique to that particular instruction. These unique interpretations are covered in the description for that particular instruction.

**Function Code (f) Designator.**—The f designator appears in bits 26-31 of a whole-word or upper half-word instruction and bits 10-15 of a lower half-word instruction, and it designates the function the instruction will perform. In addition, format II, III, and IVA instructions use a subfunction code, which provides a third digit used to further define the instruction. Any unused major function codes are considered by the computer to be illegal instructions. They cause an illegal instruction interrupt to be generated if execution of these illegal codes is attempted.

**Accumulator (a) Designator.**—The a designator appears in bits 23-25 of a whole-word or upper half-word instruction and bits 7-9 of a lower half-word instruction. The designator specifies one of the eight accumulators whose contents are to be processed by the instruction. The accumulators are contained in one of two control memory groups. These two groups are the task mode group and the interrupt mode group. Bit 10 of the active status register (ASR) indicates the group from which the accumulator contents are to be selected (0 = task group, 1 = interrupt group). For either group, the a designator addresses the accumulators as follows:

000 → A0
001 → A1
010 → A2
≈
111 → A7

**Operand Interpretation (k) Designator.**—The k designator appears in bits 20-22 of format I instructions and specifies whether a whole word or partial word is to be transferred to or from memory. When k is equal to any number other than zero, bits 13-15 specify a base register. Normal interpretation of the k designator will depend on whether a nonjump or jump instruction is to be executed.

**Nonjump Instruction Interpretation.**—In a nonjump instruction interpretation, the operand address is formed by adding the following three quantities:

1. The instruction y designator (13 bits zero extended to 16 bits)
2. The 16-bit index register contents specified by the 3-bit b designator
3. The 18-bit base register contents specified by the 3-bit s designator

The resultant operand address is Y = y + (Bb) + (Ss). The address formed by adding these quantities points to the operand, whose format is interpreted by the k designator. If the k designator specifies an upper or lower half word, that 16-bit half-word operand is sign-extended to 32 bits. If the k designator specifies a quarter word, that 8-bit quarter word is zero-extended to 32 bits. If the k designator specifies a whole word, the entire 32-bit word is used.

When a partial word operand (half or quarter word) is specified, the transfer from main memory to the arithmetic section (during a read instruction) is always to the low-order position of the arithmetic section. For half-word transfers, sign extension always takes place except as specified under the descriptions of the individual instructions. For quarter-word transfers, sign extension never occurs and bit positions 8-31 are zero filled. In transfers from the arithmetic section to main memory (store instructions), the k designator specifies the half word or quarter word of memory into which the lower order bits of the arithmetic section are transferred. When k = 0, the effective operand for a read instruction is the 16-bit sum of the 16-bit index register specified by the 3-bit b designator and the 16-bit number consisting of the s and y designators of the instruction. The resultant 16-bit sum is sign-extended to 32 bits and used as Y in the specified arithmetic operation.

**Jump Instruction Interpretation.**—Jump instructions are format III; therefore, the k designation is divided into two parts, a two bit (f3) designation and a jump operand interpretation (Z) designation bit. If (Z) = 0, the jump address is formed the same way as ordinary operand addresses. (Z) = 1 is not used.

**Index (b) Designator.**—The b designator appears in bits 17-19 of whole-word or upper half-word instructions and bits 1-3 of lower half-word instructions. The b designator specifies one of seven index (B) registers, whose contents are added to the basic operand address y to form y + (Bb). The B registers are located in one of two control memories. These two groups are the task mode group and the interrupt mode group. Bit 10 of the active status register (ASR) indicates the group from which the B register content is to be selected:

1. Bit 10 = 0, contents of B register located in task mode group

2. Bit 10 = 1, contents of B register located in interrupt mode group

For either group, the $\underline{b}$ designator is translated as follows:

000 → B0 (Do not modify $\underline{y}$)
001 → B1 (Add B1 content to $\underline{y}$)
|
≈
|
111 → B7 (Add B7 contents to $\underline{y}$)

**Base Register ($\underline{s}$) Designator.**—The base register $\underline{s}$ designator appears in bits 13-15 of whole-word instructions. It is not used in half-word instructions. It is used to specify one of eight base (S) registers, within control memory, whose contents are added to $\underline{y}$ + (B$\underline{b}$) to produce the modified operand address Y = $\underline{y}$ + (B$\underline{b}$) + (S$\underline{s}$). Bit 11 of the ASR determines whether the task mode group (bit 11 = 0) or the interrupt mode group (bit 11 = 1) of control memory will contain the S register selected. For either group the $\underline{s}$ designator is translated as follows:

000 → S0 [Add S0 contents to $\underline{y}$ + (B$\underline{b}$)]
001 → S1 [Add S1 contents to $\underline{y}$ + (B$\underline{b}$)]
|
≈
|
111 → S7 [Add S7 contents to $\underline{y}$ + (B$\underline{b}$)]

**INSTRUCTION CLASSES AND TYPES.**—Most instructions executed by the CPU are divided into one of three major classes—read (R), store (S), and replace (RP).

*Read instructions* acquire an operand from main memory but do not replace it after an arithmetic operation is performed.

*Store instructions* process an operand already acquired and store it in main memory.

*Replace instructions* acquire and process an operand and then store it in memory.

Most instructions can also be categorized by type or characteristics that are common to several instructions, regardless of their class.

*Double-length instructions* process a double-length operand, which consists of two adjacent words stored in memory (Y and Y + 1).

*Half-word instructions* consist of 16 bits of a 32-bit word. There can be two half-word instructions in a 32-bit word. If this is the case, the half-word instruction in the upper half of the word is executed first, followed by the instruction in the lower half. If only one half-word instruction occupies a 32-bit word, it must be in the upper half with all zeroes in the lower half. All format IVA and IVB instructions are half-word instructions.

*Character addressable instructions* allow certain bit fields (called characters) of an operand to be processed by the instruction. This is done in lieu of processing a whole-, half-, or quarter-word operand. Character addressing is permitted only when the instruction is executed in the indirect address mode. The particular operand bit field to be acquired is specified by the indirect address word addressed by the instruction.

*Repeatable instructions* can be programmed for reiteration by preceding them with the repeat instruction (07 6).

*Privileged instructions* are executed only when the CPU is operating in the executive (interrupt) mode. The executive mode is normally a special routine made up of instructions that direct the execution of working programs, which consist of nonprivileged instructions. These working programs allow each CPU (in a multiple CPU installation) to perform specific tasks. In this manner, these tasks can be simultaneously executed by all CPUs.

### Central Processor Unit (CPU)

The CPU contains all the internal control, arithmetic, and timing circuits required to execute instructions. The CPU receives its initial start and stop signals from either the operator panel or one of the consoles, and returns monitored signals to the console. The CPU also communicates with the main memory units (MMUs) and the input/output controller (IOC). Figure 3-17, a foldout at the end of this chapter, is a simplified block diagram of the CPU. The CPU contains the following major functional circuits: timing circuits, control circuits, and arithmetic circuits.

**TIMING CIRCUITS.**—The timing circuits of the CPU operate asynchronously with the other functional computer sections. An asynchronous computer, or unit, is one in which an operation does not depend upon a set timing sequence. Instead, it depends upon a signal indicating that the previous operation has been completed, regardless of how much time is required to reach that completion. The timing circuits for the control section consist of a master clock, a main timing chain, and a monitor clock oscillator.

**Master Clock.**—The master clock is a delay line oscillator that generates timing pulses used in the main timing chain. Two normal pulses (OA and OB) and two special purpose pulses (OA* and OBA) are generated for each cycle of the oscillator. The duration of each oscillator cycle is 240 nsec. Initiation of the oscillator operation is by means of a START signal from the operator's panel, maintenance panel, or remote console. During normal instruction execution, the oscillator can be stopped for any of several holding conditions. The holding conditions are usually caused by a reference to main memory, either to obtain an instruction or operand or to store an operand.

**Monitor Clock Oscillator.**—The monitor clock oscillator is used to decrement the contents of the central processor monitor clock register during a monitor clock sequence. The monitor clock provides for decrementing the monitor clock register by one count at a rate of 1,024 counts per second. When the monitor clock register goes to a negative number, associated circuitry detects this condition and generates an interrupt.

**Timing Sequences.**—All of the CPU operations are controlled by seven timing sequences. Each timing sequence issues a series of commands to perform a particular instruction or operation. The seven sequences are as follows:

- Instruction (I) sequence
- Indirect addressing (iA) sequence
- Operand 1 (OP1) sequence
- Operand 2 (OP2) sequence
- Monitor clock (MON CLOCK) sequence
- Console (CONS) sequence
- Interrupt (INT) sequence

All instructions executed by the CPU are made up of at least two sequences—an I sequence and an OP1 sequence. The primary functions of the I sequence are to acquire the instruction and define the operand absolute address, if required. The main purpose of the OP1 sequence is to acquire the operand and execute the instruction.

Certain types of instructions require more sequences than those just mentioned. Indirect address instructions require one or more IA sequences after the execution of the first I sequence. This allows for cascading the indirect address and holding off the instruction execution until the operand address has been determined. Replace instructions require an OP2 sequence to store the results of the instruction processed during the OP1 sequence. Interrupts are processed when they occur by an INT sequence.

**Sequence Control.**—The four sequences associated with instruction execution (I, IA, OP1, and OP2) are each generated by means of a sequence logic circuit upon initiation of the applicable sequence-request enable. For a particular instruction, each sequence is generated on successive MT clock cycles. The sequence logic circuits for the four sequences are similar. The only difference is the signals that are used to directly activate a particular sequence.

**Sequence Enables and Holds.**—The activating of sequence-request enables permits the issuance of the sequence signals needed to execute the instruction. These enables, one for each sequence, are activated in one of two situations:

1. In the absence of any condition that would suspend normal instruction execution; or
2. Upon activation of a signal requesting a sequence-request enable to occur at some time other than the normal program sequence.

The sequence-request-enable logic generates request-enables for the I, IA, OP1, and OP2 sequences for normal instruction execution and program operating conditions. The I SEQ REQ EN signal is generated continuously in the absence of any inhibiting conditions. These conditions are instruction address fault, maintenance console operations, programmed stop, MON clock sequence, repeated instructions, double-length instructions, privileged instructions, execute remote instructions, and lower half-word instructions. The I SEQ, in turn, generates the OP1 SEQ REQ EN on the next MT clock cycle. These two sequences (I and OP1) are necessary for executing all instructions. The signal IA SEQ REQ EN is generated whenever an instruction requiring indirect addressing is executed. The signal OP2 SEQ REQ EN is generated for special instructions or conditions. For example, a DOUBLE LOAD Aa instruction, where two accumulators are being affected, requires an OP2 sequence.

The console sequence (CSL SEQ) is used to gate data either into or out of the CPU by way of the maintenance panel. The CSL SEQ consists of four CPU master clock cycles. The CSL SEQ is enabled and disabled by way of the RUN f/f. In the run condition, the CSL SEQ is disabled.

**CONTROL CIRCUITS.**—The control circuits of the CPU consist of all the registers, translators, selectors, adders, and comparators required to acquire and translate an instruction word. After translation, signals are sent to the arithmetic circuits when an instruction requires that an arithmetic function be performed, or signals are sent to the IOC if an I/O instruction is to be translated. Control signals are also routed to memory to acquire or to store operands.

**Instruction Timing.**—The timing of instruction execution in the control portion of the CPU is determined by the KE, AK, K, and K* registers (AK upper and lower, and K upper and lower). Enables for the various operations (transfers, arithmetic, and shifting) are controlled by the counts in these registers. You can find detailed timing diagrams in SE610-AW-MMA-010, *Maintenance Manual for Computer Set AN/UYK-7(V).*

**Instruction Acquisition.**—Instructions can be acquired from either main memory or NDRO (ROM) memory contained within the CPU. During normal program operation, all instructions are obtained from main memory. Instructions contained in the ROM are obtained when ASR bit 7 = 1 and base register 7 is specified. Base register 7 in this condition is not interpreted; instead, the instruction is read out of the ROM. This condition is achieved by a hardware fault program using the bootstrap load procedure, or it can be selected by programming. Instructions to be read from main memory stop the main timing chain after the address of the instruction is loaded on the I bus data/address lines. The main timing chain remains stopped for the time necessary to read out the instruction from memory and place it on the I bus. From the I bus, the instruction word is transferred to the U upper (UU) and U lower (UL) registers.

**U Register.**—The U register is a 32-bit register that holds the instruction word to be translated prior to execution. It is composed of the 16-bit U upper (UU) register and 16-bit U lower (UL) register. The UU register contains the instruction function code and designators, and the UL register contains the main memory address of the operand to be processed. When the next instruction to be read from memory is a half-word instruction (format IVA or format IVB), one 32-bit word containing two sequential half-word instructions or one half-word instruction in the upper half of the word is read and transferred into the UU and UL registers. The first half-word instruction contained in the UU register is translated for its function code and instruction designators. Upon execution of the first half-word instruction, the second half-word instruction is shifted from the UL to UU. This instruction is then translated and executed.

**U Translator.**—The U translator translates function codes before they would normally be needed (as with the V and F translators) to initiate certain preliminary operations connected with instruction execution (such as aborting an illegal instruction before index (B) and base (S) register modification and determining the instruction word format).

**V Selector.**—The V selector (V SEL, fig. 3-17) is part of the V translation circuitry. It gates data from the UU register into the V register.

**V Register.**—The V register (V RGTR, fig. 3-17) is a 23-bit register that holds the data from the UU register for translation by the V translator.

**V Translator.**—The V translator (V XLTR, fig. 3-17) provides a full translation of all computer instructions in the form of unique function codes. It translates the upper 6 bits of the V register to produce the two unique function code octal digits, and then adds an appropriate subfunction code octal digit by way of a word format indicator derived from bits V15-12. The derived function codes are routed to other parts of the control section of the CPU to execute the instructions.

**F Register.**—The F register (F RGTR, fig. 3-17) is a 21-bit register that contains function code data loaded into it from the V register. This data is used by the F translator.

**F Translator.**—The F translator (F XLTR, fig. 3-17) is basically the same as the V translation logic with two exceptions: (1) the F translation occurs later than the V translation to allow execution of overlapped instructions; and (2) the format designators F15-12 are applied to the octal translator stages.

**Instruction Translation.**—The translation of each instruction code involves decoding the upper 6 bits of the instruction contained in the UU register into two octal digits, which define the instruction code. If the instruction being executed is a format II, III, or IVA instruction, an additional 2 or 3 bits are decoded to generate the third octal digit ($\underline{f}2$, $\underline{f}3$, or $\underline{f}4$) necessary to define these instructions. These function codes are then routed to the other parts of the control section logic, either as unique codes or "ORed" together in certain combinations, to execute the instruction. The function code translation is performed by the U translator, V translator, and F translator described previously.

**P Register.**—The P register (P RGTR, fig. 3-17) is the 19-bit program address register. It holds the address of the next instruction to be executed. It contains a 3-bit base designator Ps and a 16-bit relative program address P$\underline{d}$. Bit 16, the "i" bit, is always zero. After an instruction has been acquired and transferred to the U register, the content of the P register is incremented by an ADVANCE P to the address of the next instruction.

**Advance P.**—An ADVANCE P operation is performed during every instruction (I) sequence to form the address of the next instruction. During normal operation, the ADVANCE P operation increments the instruction address (P$\underline{d}$) contained in the P register by 1 so that the next sequential instruction is read.

The following logic components are used in an ADVANCE P operation: P register; U, R, and P selector; index adder; H register; C register; base adder; Y register; and P* register.

U, R, P Selector. The U, R, P selector (U, R, P SEL, fig. 3-17) is made up of logic that gates data from either the UL register, R register, or P register into the index adder. The register selected is determined by the type of modification that is to be performed: advance P (modify instruction address contained in the P register), modify Y (modify operand address contained in the UL register), or repeat operations.

Index Adder. The index adder (ADD 1, fig. 3-17) is a one's complement adder that serves the following functions:

- It adds one to the instruction address (P$\underline{d}$) from the P register during an ADVANCE P operation to form the address of the next instruction.

- It adds the contents of the selected B register to the basic operand address from the UL register during an indexing operation.

- It increments and decrements during repeat operations.

- It decrements the monitor clock register during monitor clock update operations.

The resultant 16 bits of data from the index adder are routed to the base (S) register adder (add 2, fig. 3-17) for further processing.

H Register. The H register (H RGTR, fig. 3-17) is a 19-bit holding register used to hold the incremented relative P address until the address can be gated back to the P register by way of the

C register. The H register is also used to address the ROM for instructions and operands.

C Register. The C register (C RGTR, fig. 3-17) serves as an interface register between the following sections of the CPU: arithmetic section to control section, control memory to control section, and between registers of the control section itself. The C register is a 32-bit register. It receives input data from the Q selector, B, BP, S, P, Y, H, A, MLO, ICW, DSW, status registers, and adder 1 (index adder). It transmits data to the Q selector, B, S, P, R, U, A, MLO, ICW, DSW, and status registers.

Base (S) Register Adder. The base (S) register adder (ADD 2, fig. 3-17) is a two's complement adder used to add the contents of a selected 18-bit base (S) register to the 16-bit data received from the index adder.

Y Register. The Y Register (Y RGTR, fig. 3-17) is a holding register for making instruction and operand breakpoint comparisons. It is an 18-bit register that receives the modified instruction or operand address from the base adder.

P* Register. The P* register (P*, fig. 3-17) is an 18-bit register that holds absolute instruction addresses. Information from the Y register forms the P* register's absolute instruction addresses. The address in the P* register is gated out on the I bus at instruction (I) request time.

Indexing.—Indexing is the process of modifying the operand address contained in the UL register. It consists of a modify y operation where the basic operand address (y) is modified by adding the contents of one of 14 index (B) registers reserved for modify y operations and/or one of 16 base (S) registers contained in control memory. The index operation consists of adding two or more of the following quantities:

- The basic operand address (13 bits zero-extended to 16 bits)
- The least significant 16 bits of the index register selected by the (b) designator in the instruction word.
- The 18-bit base (S) register selected by the 3-bit instruction (s) designator

The selection of a particular B or S register is determined by the instruction b and s designators by way of the B address selection logic and the S address selection logic. The modify y operation occurs during every I sequence.

**OPERAND ACQUISITION.**—The operand may be acquired from either main memory or the nondestructive readout (NDRO). In either case, operand acquisition is similar to instruction acquisition. If the operand is to be acquired from main memory, the modified operand address from the base adder is loaded into the M register and transferred out on the OP bus to main memory. The control section clock is stopped and the operand is read from memory by a memory read cycle, placed on the OP bus, and routed to the M register. If an operand is to be read from the NDRO, the H register, which holds the ROM address, enables the NDRO address. The operand is read from the ROM into the M register, and the operand is transferred into the arithmetic section to be processed.

Operands may also be acquired from the control memory part of the control section. These operands are normally acquired as part of the I sequence modify y and comparison operation. For some instructions, these control memory operands are also acquired for indexing purposes or main memory storage. These operands are not processed in the arithmetic section.

The M register (M RGTR, fig. 3-17) is a 32-bit register that functions as an operand interface register between the CPU and main memory. It transmits or receives an operand address or an operand from either the control section or the arithmetic section. The M register is connected to the bidirectional operand (OP) data bus.

**INSTRUCTION CONTROL.**—Execution of all instructions involves certain control functions that are common to many instructions. These functions include breakpoint comparisons, memory lockout comparisons, status register bit settings, and control operations associated with repeat instructions.

The breakpoint comparisons are made during the I, OP1, OP2, or IA sequence of every instruction. The BREAKPOINT COMPARE logic compares the preset 20-bit contents of the BREAKPOINT register (fig. 3-17) with the contents of the Y register. During the I sequence, the breakpoint register contents are compared to the instruction address contained in the Y register. The contents of the breakpoint register are compared to the modified operand address contained in the Y register during the OP1, OP2, or IA sequence. Bits 18 and 19 of the breakpoint register designate which type of operation is to be performed—an instruction operand compare, operand address compare, or both. Bits 0 through 17 define the instruction operand comparison address. When an address match is detected, the CPU performs the following operations, depending on the position of the BREAKPOINT PROGRAM/MANUAL switch on the maintenance panel:

- In the program mode, the CPU sets the class II breakpoint match interrupt.
- In the manual mode, the program halt occurs.

The memory protection logic consists of the *memory lock-out* compare circuitry (MLO COMPARE, fig. 3-17), the segment identification register (G CM RGTR, fig. 3-17), the storage protection register (G CM RGTR, fig. 3-17), and the base (S) register previously discussed. The memory protection logic prevents the CPU, while in task state, from accessing main memory outside the assigned address area during a read, indirect address, or write operation. Memory protection operations are performed for instruction access in the I sequence, and operand access during the OP sequence or indirect addressing during the IA sequence. The block of memory assigned during operations is defined by the base (S) register and its associated storage protection register. The (S) register contains an absolute address, which specifies the lower limit of the block of memory that is to be used. The storage protection register specifies the length of the memory block and the type of function that may be executed in the defined memory block. When the memory lock-out compare logic determines that a function not permitted by the instruction word is being attempted, a class II read, write, indirect address, operand, or instruction limit interrupt signal is generated by way of appropriate interrupt logic.

The active status register (ASR, fig. 3-17) is a 23-bit register that indicates the status of the CPU. These status indicators are used to control execution of the current instruction and succeeding instructions after an interrupt subroutine has been processed. Status indicator bits 14 through 0 are *program* controlled. Status indicator bits 22 through 15 are *hardware* controlled.

**Interrupts.**—An interrupt is either an externally or internally generated signal that signifies an event has occurred that demands immediate processing. Interrupts can occur either asynchronously or in synchronization with the CPU program. An interrupt suspends the normal program sequence and causes a jump to interrupt entrance address of a corresponding interrupt processing routine stored in memory. This jump is performed during an interrupt sequence, which inhibits the normal program I sequence. All interrupts have priority over the normal program, and the interrupts themselves are ranked by priority. Priority is established by dividing the interrupts into four separate priority classes and assigning priorities to each interrupt within a particular class. The four classes of interrupts are listed below:

Class I —power tolerance fault and hardware fault interrupts

Class II —program error interrupts

Class III—I/O interrupts

Class IV—executive interrupts

Class I interrupts are generated to indicate a power tolerance fault or hardware fault errors. Class II interrupts are generated by the CPU and indicate the following program errors:

- Floating point error
- Illegal instruction
- Privileged instruction error
- Operand breakpoint
- Operand read or indirect addressing
- Operand write
- Operand limit

- Instruction breakpoint
- Instruction execute
- Instruction limit
- Monitor clock
- Interprocessor interrupt

Class III interrupts include input/output interrupts that occur independent of the task being performed at the time of the interrupt. All class III interrupts are generated by the IOC. Some of the class III interrupts are as follows:

- IOC illegal instruction
- IOC processor interrupt
- IOC monitor clock
- External interrupt monitor
- External function monitor
- Output data monitor
- Input data monitor

A class IV interrupt is generated by an *enter executive state* instruction and is used to turn control over to the executive program.

**Control Memory.**—The *control memory* (CM) is a random-access flip-flop memory consisting of 82 addressable storage registers. Access to CM data requires less time than access to main memory, and it is performed as part of a control section sequence while the master oscillator is running. The register assignment of the CM is as follows:

- Accumulator (ACC) registers—two sets of eight ACC registers, 32 bits each
- Index (B) registers—two sets of seven B registers, 19 bits each
- Base (S) registers—two sets of eight S registers, 18 bits each
- (G) Registers—one set of eight 21-bit, storage protection registers, and one set of eight 19-bit segment identification registers.
- Miscellaneous CM consisting of designator storage words (DSWs) registers—one set of 16 DSW Reg, 20 bits each

  initial control word (ICWs) registers—one set of four ICW Reg, 20 bits each
- Breakpoint (BP) register—one register, 20 bits
- Active status register (ASR)—one register, 23 bits
- Central processor monitor clock register (CPMCR)—one register of 19 bits
- Designator storage word (DSW) register—one set of 16 DSW Reg, 20 bits each
- Segment identification registers—one set of eight SIRs, 21 bits each

The CM registers are divided into two groups—a task mode group and an interrupt mode group. Addressing a register in a particular group (a register group, DSW, or ICW group) is accomplished by way of the selection logic for that particular group. There is only one breakpoint and active status register, and these registers are addressable only in the interrupt mode.

**Nondestructive Readout (NDRO) Memory.**—The NDRO (fig. 3-17) of the CPU is a 512 or 1,024 word memory, which is contained in an enclosed module. Programming the NDRO is accomplished at the time of manufacture and cannot be altered except by removing it and replacing it with another NDRO assembly. Contents of the NDRO are electrically unalterable. The NDRO is tailored to system requirements but usually contains the following standard programs:

- Two bootstrap programs used to load programs from two peripheral equipments into main memory

- A class I interrupt program that is entered when a class I interrupt occurs (except power tolerance)
- Three diagnostic programs—a load failure analysis program, a memory test program, and an interface test program
- An auto start program
- A CPU start program
- An inspect and change program

Selection of a particular word in the NDRO is by means of the NDRO address select, line selector, and current switch logic. The switch logic is fed from the H register described previously. Bits 5, 6, 7, and 8 of the H register cause one of 16 current switches to be activated, and bits 0 through 4 enable one of 32 lines. This selects any one of $512_{10}$ addresses. The $1024_{10}$ address NDRO uses bit 9 of the H register to select the upper or lower $512_{10}$ addresses. Selection of the address in these blocks is accomplished as described for a 512 10 address ROM.

**ARITHMETIC CIRCUITS.**—The arithmetic section of the CPU contains the logic circuits to perform the various mathematical, logical, or shift operations required by a computer instruction. The CPU can perform computations in a fixed point or floating point format. The following paragraphs describe the timing and function of the arithmetic portion of the CPU.

**Shift Count Register Selectors.**—The shift count register selector (SCR SEL, fig. 3-17) evaluates the instruction conditions and timing and selects the shift count source from the Q selector or the V translator. Q selector bits 0-5 can be gated through the SCR selector in either true or complement form. Bits 21-16 or 25-20 from the V translator can be gated through the SCR selector.

**Shift Count Register.**—The shift count register (SCR, fig. 3-17) is a 6-bit, double rank register that holds the shift count and provides the count translation for all shifting operations. The shift count contained in the shift count register cannot exceed 63. The lower rank of the SCR can be loaded from either the D selector or the SCR selector. The upper rank can only be loaded from the D selector. The shift count translation is made from the lower rank. Because the shift network can provide only a left shift count, the translator complements the count when a right shift is enabled. For example, when a right shift of 16 is specified, the translator provides a count of 47 to the shift register. The 47-place left shift, with a left one correction, is equivalent to a 16-place right shift. When no shift is enabled, the translator provides a zero shift output.

**Shift Network.**—The shift network (fig. 3-17) is a three-level selection matrix, 64 bits per level, which permits shifting zero through 63 places in one pass through the matrix. Data from either the D or Q selectors can be gated into the shift network. The first level shifts the selected data 0, 16, 32, or 48 places as determined by the translation of SCR bits 4 and 5. The second level shifts the data from the first level 0, 4, 8, or 12 places as determined by the translation of SCR bits 2 and 3. The third level shifts the data from the second level, 0, 1, 2, or 3 places as determined by the translation of SCR bits 0 and 1. The shift network provides for circular, sign maintained, and zero-filled shifts. For single register circular shifts, both the D and Q selectors gate the same data into the shift network.

**Arithmetic Timing.**—The arithmetic portion of the CPU operates asynchronously with the other functional computer sections. The sequence of operations for instructions using arithmetic circuits are controlled by two sets of timing signals. The primary timing (clock timing) is generated by three semi-independent delay line circuits. The clock timing can generally be considered self-regenerating. The secondary timing (counter timing) is produced by means of double-rank counter registers. The counter signals provide sequence, iterative, and control memory address control.

Three counter registers generate timing signals used by the arithmetic portion of the CPU. They are the K counter (KU and KL), K* counter (K*U and K*L), and AK counter (AKU and AKL). The timing signals provided by the 12-bit K register are used to initiate delay lines, control transfers between arithmetic registers and selectors, control shift direction, and activate conditional detection circuits. The 6-bit K* register is the iteration counter and provides timing signals for control memory address generation and for disabling the advance of the K register. The upper rank of the K* register (K*U) is initially loaded with bits 25-20 from the V translator. The count in K*U is transferred to K*L at time AT0D (clock timing) and with subsequent AT1C (clock timing), incremented by one and returned to K*U.

The 5-bit AK register provides timing primarily for Q selection control and control memory accumulator address selection. This permits proper sequencing of the access and storage of data in the control memory accumulator. When the START ARITHMETIC signal is present, the content of AKU is transferred to AKL. Thereafter, each time an 80-nsec signal from clock timing is sent to the AK register, each bit of AKL is transferred to the next most significant bit in AKU. AKU is then transferred straight back to AKL (bit-for-bit), and the process of transferring AKL back to AKU (one bit over) continues. This results in a left shift of the data in AKU. When the last instruction sequence reference to the accumulator has been made, the AK register is disabled. The AKU register is cleared whenever a timeout or master clear occurs.

**X Register.**—The X register (X RGTR, fig. 3-17) functions primarily as an operand holding register and can be loaded from either the M register, the Q selector, or the W selector. The X register can be either set to all ones or cleared to all zeros by command. The contents of the X register are fed to the X selector.

**X Selector.**—The X selector (X SEL, fig. 3-17) provides for the selection of one of four magnitudes from the X register to the subtractor. The four operand magnitudes are X, $\overline{X}$, 2X, and $\overline{2X}$. The true form X value provides a difference at the subtractor output while the complement-form X value ($\overline{X}$) provides a sum. The 2X and $\overline{2X}$ values are used primarily in a multiply operation. The 2X and $\overline{2X}$ values are the true and complement forms of X and $\overline{X}$ scaled left one bit position by the selector to increase the magnitude by a factor of 2.

**D Register.**—The D register (D RGTR, fig. 3-17) receives either the subtractor output or the contents of the A or W register. The contents of the D register are available to the W selector, W register, D selector, or Q selector. The D register can be set to all ones or cleared to all zeros by command.

**D Selector.**—The D selector (D SEL, fig. 3-17) provides for transfer of data from Q register, D register, or M register to either the shift network or, for bits D 29-20 only, the shift count register.

**Q Register.**—The Q register (Q RGTR, fig. 3-17) receives the subtractor output, the exclusive OR output of the subtractor, or data from the Z register. The Q register can be set to all ones, or cleared to all zeros by command. The contents of the Q register are available to the Z selector, W selector, D selector or Q selector.

**Q Selector.**—The Q selector (Q SEL, fig. 3-17) provides for transfer of data from the Q register, D register, or M register to the shift network, X or C registers, SCR selector, display console register or an accumulator register. Test logic for QS = 0 is also included in the Q selector.

**W Register.**—The W register (W RGTR, fig. 3-17) receives either the true or complement form data from the W selector, or data from the D register. The contents of the W register are available to either the D register or the subtractor selector. The W register can be set to all ones or cleared to all zeros by command.

**W Selector.**—The W selector (W SEL, fig. 3-17) provides for transfer of data from the D or Q registers, or the shift network (either directly or scaled left one bit position) to either the W, X, or M register.

**Z Register.**—The Z register (Z RGTR, fig. 3-17) receives either the true or complement form data from the Z selector. The contents of the Z register are available to either the Q register or the subtractor selector. The Z register may be set to all ones or cleared to all zeros by command.

**Z Selector.**—The Z selector (Z SEL, fig. 3-17) provides for transfer of data from the accumulator (A) register, Q register, or the shift network (either directly or scaled left one bit position to either the Z register or the M register).

**Subtractor.**—The subtractor (SUB, fig. 3-17) is a static logic network that accepts signed 32-bit words in parallel from the subtractor selector (minuend) and X selector (subtrahend) and forms the ones-complement integral difference. The difference can be displayed in either the D register or the Q register. Addition is performed by subtracting the addend (complement form) received from the subtractor selector from the augend (either true or one's complement form) received from the X selector.

The 32-bit subtractor is organized into eight four-stage groups. Within each group are the two half adders for each stage, the interstage and intergroup borrow logic, and the circuit that determines if the three least significant output stages are equal to zero. The borrow logic can generate an end-around borrow when required. The end-around borrow can be either disabled or forced, as instruction conditions indicate. An exclusive OR output of the first half-adder operation is used with logical instructions.

**Subtractor Selectors.**—The subtractor selector (SUB SEL, fig. 3-17) is a simple gating network that provides the minuend (or augend) to the subtractor. The minuend can be selected from either the W register or the Z register in either true or complement form.

**Arithmetic Operations.**—Arithmetic operations are composed of a series of data shifts or transfers and one or more add or subtract operations. The *add process* involves complementing the addend and subtracting it from the augend, resulting in the sum of two numbers.

The *divide operation* is based on a process that performs a one-place left shift and a trial subtraction of the divisor in the X register from the most significant half of the dividend in the W register. If the trial subtraction does not cause an end-around borrow to be generated, a one is placed in the least significant bit of the developing quotient in the Q register, and the resulting difference becomes the most significant half of the current dividend for the next step. If the trial subtraction causes an end-around borrow, a zero is placed in the least significant bit of the developing quotient and the half of the dividend operated upon is restored.

The process operates on a positive dividend, and the quotient developed is a positive number. The value of the divisor is always gated to the subtractor as a positive number. The sign of the quotient in Q is corrected, and the sign of the remainder is corrected to the sign of the original dividend after the last iteration if a negative number was used in the operation. Zero testing, parity checks, and count ones functions are also performed by the arithmetic portion of the CPU.

### I/O Controller

The IOC (fig. 3-11) functions as a communication controller for the computer set. It routes all data to and from the computer. The word formats used to control the IOC and its timing and control logic will be discussed in the following paragraphs.

**IOC WORD FORMAT.**—The IOC has four word formats for control and routing of data to and from peripheral equipment, main memory, and the CPU. The four words used by the IOC to perform its tasks are as follows:

1. I/O command word
2. IOC control memory word
3. Normal buffer control word
4. Externally specified index control word

**I/O Command Word.**—The I/O command word (fig. 3-18) is a 32-bit coded instruction word

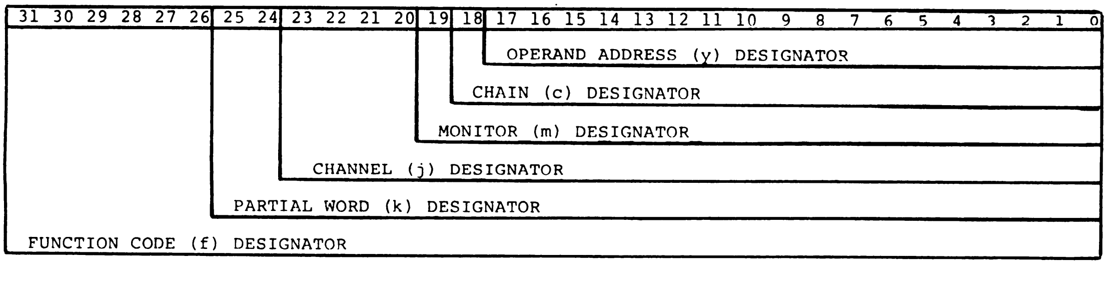


**Figure 3-18.—I/O command word format.**

that defines the particular I/O command to be executed. The I/O command word can be broken down into six designators: f, k, j, m, c, and y.

1. The (f) designator defines the I/O command to be executed.
2. The partial word (k) designator defines whether a whole or partial word is transferred into or out of memory.
3. The channel number (j) designator specifies the I/O channel ($0\text{-}17_8$) associated with a particular I/O command.
4. The monitor (m) designator specifies whether or not the transmission of a monitor interrupt occurs following termination of a buffer.
5. The chain (c) designator specifies whether or not another I/O command is executed following termination of the current operation.
6. The operand address (y) designator specifies the address location of the data that forms the control memory words buffer current address and buffer final address designators for any buffer function instruction.

**Control Memory Word.**—The control memory word (fig. 3-19) is a 56-bit coded word that controls the transfer of data for I/O buffer functions. The control memory word format has seven designators: CAP, k, c, m, by, bfa, and bca.

1. The command address pointer (CAP) designator specifies the address of the next I/O command providing the c designator is set.
2. The partial word (k) designator specifies whether a whole or partial word is transferred into or out of memory.
3. The chain (c) designator specifies whether or not another I/O instruction is to be executed following the termination of the current operation.
4. The monitor (m) designator specifies whether or not the transmission of a monitor interrupt occurs following termination of a buffer function.
5. The byte (by) designator functions with the k designator in transferring either whole or partial words into or out of memory. The by designator is incremented by one after each portion of a partial (half, quarter) word transfer, and it increments the buffer current address after completion of a partial word transfer.
6. The buffer final address (bfa) designator defines the address of the last word transferred for a particular buffer function.
7. The buffer current address (bca) designator defines the address of the initial or current word transferred for a particular buffer function.

The normal buffer control word is 32 bits in length, broken into two fields. The first field, bits 0-17, holds the address of the first word to be transferred to or from main memory and the peripheral equipment. The second field, bits 18-31, is the final address of the data that will be transferred.

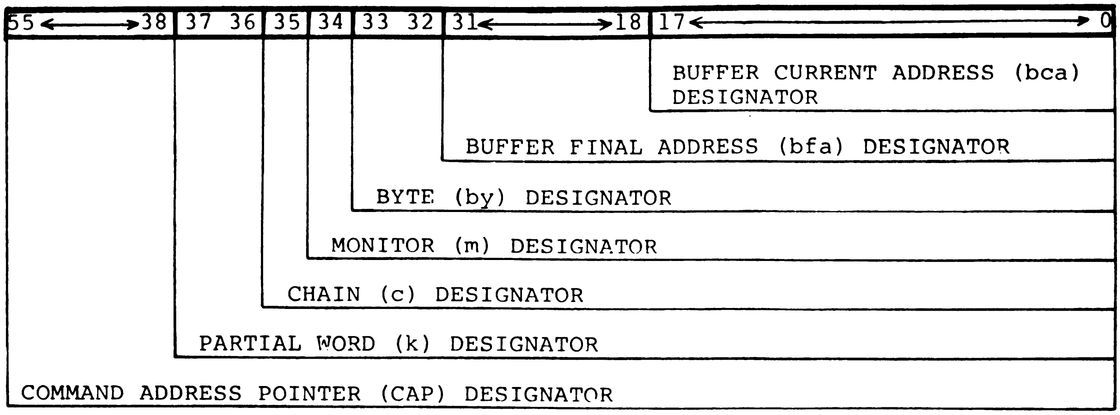

55 ⟷ 38
37 36
35
34
33 32
31 ⟷ 18
17 ⟷ 0
BUFFER CURRENT ADDRESS (bca) DESIGNATOR
BUFFER FINAL ADDRESS (bfa) DESIGNATOR
BYTE (by) DESIGNATOR
MONITOR (m) DESIGNATOR
CHAIN (c) DESIGNATOR
PARTIAL WORD (k) DESIGNATOR
COMMAND ADDRESS POINTER (CAP) DESIGNATOR

Figure 3-19.—Control memory word format.

**Externally Specified Index (ESI) Mode.**—The ESI mode is used by peripheral equipments to specify an index address in main memory. As in the ESA mode, only the lower 65K of main memory is used for storing ESI control memory words. ESI data transfers are identical to normal buffer data transfers except the IOC requires that the external device specify a 16-bit index address in main memory, at which the buffer control word is located. The index address is contained in the ESI request word, which also contains the 16 bits of data to be stored when the ESI operation is an input data or external interrupt operation.

**IOC TIMING.**—The timing pulses required to synchronize operations in the IOC are generated by the IOC main timing logic. The timing logic consists of the *IOC master clock* and *IOC main timing*. The main timing logic is driven by clock pulses from the master clock. The timing logic produces and distributes timing signals to all of the IOC control logic.

**IOC Master Clock.**—The IOC master clock is a 240-nsec delay line oscillator having taps at 40-nsec intervals. The outputs of the delay line taps are ORed together to produce five pulses: 01, 02, 03, 04, and 02L. The clock pulses are "ANDed" with main timing pulses and with other control signals to sequence IOC operations. Clock signals 01 and 02 also are used to synchronize the generation of main timing signals.

**IOC Main Timing.**—The IOC main timing logic produces up to eight 240 nsec wide timing pulses designated T11 through T42, one extended sequence (360 EN1), and combinations of master clock and main timing pulses designated T1101 through T4202. The timing pulses are generated by a chain of eight flip-flops and associated logic gates. The flip-flops are connected so that the output of one flip-flop sets the next flip-flop and clears the one behind. For example, the output of T21 sets T22 and clears T12. Setting and clearing each flip-flop is synchronized by master clock pulses 01 and 02. Phase 1 controls the generation of T12, T22, T32, and T42. Phase 2 controls the generation of T11, T21, T31, and T41. T41 and T42 are not used for all functions of the IOC and, therefore, are not always generated. When T41 and T42 are used, the reinitiation of the timing is delayed by 240 nsec. A complete cycle of main timing pulses is 720 nsec, if T41 and T42 are not run, and 960 nsec if they are run.

**IOC Cycle Counter.**—The IOC cycle counter keeps track of the number of times the IOC main timing chain cycles during the execution of a sequence. The longest sequence, an ESI buffer sequence, requires four cycles. The cycle counter consists of two ranks of four flip-flops each.

**K Counter.**—The K counter produces timing pulses used to enable initial operation events. The K counter consists of five flip-flops and associated gates. The outputs of the flip-flops are ANDed with main and cycle timing pulses. The K counter is used in conjunction with main timing and the cycle counter to enable and disable various flip-flops.

**IOC CONTROL CIRCUITS.**—The control circuits of the IOC consist of program and operation control logic. All circuits are directly or indirectly controlled by program control. The program control circuits decode I/O commands from the CPU and generate the signals required to execute the instruction. Program control circuits consist of the active registers, monitor registers, real-time clock, monitor countdown clock, interrupt lockout registers, command address register, command interface register, I/O mode selector, and the decoder.

The operation control circuits consist of the main memory address register, the control memory, the control memory address register, the ± 1 adder, the buffer sequence enable logic, the data interface register, and the status code register. The following paragraphs discuss the function of the program and operation control circuits.

**Active Registers.**—The active registers (fig. 3-20, a foldout at the end of this chapter) indicate the function of channels that have established a buffer area and are ready to execute data transfers. There are four types of active registers—input, output, external function, and external interrupt. Each active register contains 16 bits (one per channel). Active registers are set and cleared under program control. Execution of IOC buffer commands (10 through 13) set the active registers. In addition to being cleared under program control, the active registers are also cleared when the buffer is full (upper and lower portions of the control memory word compare, U = L).

Leave figure 3-20 folded out, and refer to it as you read about the following parts of the IOC.

**Monitor Registers.**—The IOC monitor registers indicate the function of channels requesting a monitor interrupt. There are four types of monitor registers—input, output, external function, and external interrupt. Each monitor register contains 16 bits (one per channel). A monitor interrupt is performed following termination of a function buffer if the associated function monitor bit is set. Monitor registers are set and cleared under program control. Execution of the IOC buffer terminate command (14) clears monitor registers. The monitor registers also clear after completion of the monitor interrupt.

**Real-Time Clock.**—The real-time clock (RTC) is a 32-bit register that is incremented by one during each RTC sequence. The RTC is incremented at a rate determined by selecting either an internal or an external oscillator. The internal oscillator increments the RTC at a rate of 1.024 kHz. The external oscillator can increment the RTC up to a maximum rate of 100 kHz. The RTC INT/EXT switch on the operator panel selects the timing source used. The ± 1 adder is used to perform the RTC increment operation.

**Monitor Countdown Clock.**—The monitor countdown clock is a 16 bit register that deactivates when entered with a negative value. When entered with a positive number, the monitor countdown clock decrements the count to zero at a rate determined by the internal or external oscillator. The ± 1 adder is used to perform the monitor clock decrement operation. The monitor countdown clock is decremented during each RTC sequence if the value held in the clock is not negative. When the monitor clock passes through zero to a negative number, a class III interrupt is generated to all the CPUs connected to the IOC.

**Interrupt Lockout Registers.**—The interrupt lockout registers indicate the I/O channels for which a CPU receives monitor interrupts. There are three interrupt lockout registers, one for each of the three CPUs to which an IOC may be coupled. Each interrupt lockout register has 16 bits (one per channel). The interrupt lockout registers are controlled by processor instructions. Any bit (channel) of an interrupt lockout register sets when the interrupt enable instruction (07 1) is executed. Execution of the interrupt disable instruction (07 2) clears any bit (channel) of an interrupt lockout register selected.

**Command Address Register.**—The command address register (CAR) receives an I/O command address from a CPU. There are three command address registers, one for each CPU. The command address is transferred to the main memory address register (MMAR). From the MMAR, the command address initiates an I/O command by reading the command specified by the command address from memory and by beginning its execution. If the I/O command executed is a buffer instruction (10 through 13), the command address held in the CAR is incremented by one to form a command address pointer (CAP), and then it is stored in control memory. If the I/O command executed is not a buffer instruction and the chain bit (c) is set, the CAR accesses the next instruction of a chain operation.

**Command Interface Register.**—The command interface register transfers interrupt entrance and command information between the CPU and IOC. From the IOC, the command interface register transfers interrupt entrance information generated by the monitor and external interrupt functions to the CPU. From the CPU, the command interface register transfers command addresses to the CAR in the IOC.

**Decode.**—The decode circuit generates the control memory addresses used to access data stored in control memory. These control memory addresses are formed by data interface register bits 27 through 20. The decode circuit forms the control memory addresses as part of I/O command execution.

**I/O Mode Selection.**—The I/O mode selector is a prewired module which determines the operating mode, the intercomputer time-out period, and the rotation priority for each of the 16 I/O channels. The module is wired at the time of manufacture for the particular system configuration specified, and is not normally changed. Any one of the four I/O modes (normal, ESA, ESI, or intercomputer) may be selected for any of the 16 I/O channels.

**Main Memory Address Register (MMAR).**—The MMAR holds an 18-bit address used to read from and store data into main memory. This address is formed by one of the following: buffer current address (bca), command address pointer (CAP), data interface register contents, or CAR contents. The buffer current address specifies the location of the current I/O word to be read from or stored into main memory. The CAP designates the location of the next I/O command to be performed if the chain designator is set. The contents of the data interface register specify the address of the ESA word to be buffered, the address of the ESI, the ESI buffer current address location, the address of a word to be loaded into control memory when performing a load IOC control memory instruction (24), or the address of a new RTC count to be accessed when performing an enter RTC (23) instruction. The CAR contents specify the address of the I/O command performed by the IOC as obtained from the CPU initiate I/O (07 4) instruction.

**Control Memory.**—The control memory stores sixty-four 56-bit control memory words. These words are used to control data transfers for I/O buffer functions. There are four I/O functions: input, output, external interrupt, and external function. Each I/O function is allocated 16 control memory words (one per channel). Address assignments for the I/O buffer functions are as follows:

| | |
|---|---|
| 1. Input | $00_8$-$17_8$ |
| 2. Output | $20_8$-$37_8$ |
| 3. External function | $40_8$-$57_8$ |
| 4. External interrupt | $60_8$-$77_8$ |

Transfer of control memory words to their assigned control memory locations is performed by the data interface register. These transfers occur during I/O command execution.

**Control Memory Address Register.**—The control memory address register holds a 6-bit address used for addressing each of the 64 control memory locations. Request, chain, and monitor priority logic supply the control memory addresses during buffer function operations. Control memory addresses are also generated by the decode logic during I/O command execution.

**± 1 Adder.**—The ± 1 adder provides a means of updating the contents of registers contained in the IOC by either + 1 or − 1. The + 1 data path updates the RTC, the CAR, and the MMAR. The − 1 data path updates the monitor countdown clock.

**Buffer Sequence Enable Logic.**—The buffer sequence enable logic controls the logic of the I/O adapter. The buffer sequence enable logic generates channel group and function enables. These enables determine the output registers, input receivers, and acknowledge signals issued from the adapter. The buffer enable sequence logic is supplied information from the control memory address register during the buffer sequence of any given function's buffer. During the execution of an I/O command, the decode logic supplies information to the buffer enable sequence logic.

**Data Interface Register.**—The data interface register transfers I/O commands and data between the IOC and main memory. I/O data is transferred either from the IOC to main memory or from main memory to the IOC. These data transfers occur during the buffer sequence of any I/O function. The buffer current address of a particular I/O control memory word specifies the location in main memory to be accessed for the data transfer. I/O commands are transferred from main memory to the IOC by means of the data interface register from the I/O memory bus. The MMAR holds the address of the I/O commands read from main memory during an I sequence.

**Status Code Register.**—The status code register holds interrupt status codes (ISCs), which are generated by the monitor priority circuits.

A particular ISC is generated for each IOC interrupt request. The ISC is transferred to the CPU generating the request by means of the command interface register and the O bus.

**I/O CONTROLLER OPERATIONS.**—The operation of the IOC is divided into five parts for ease of explanation: operation description, standard functions, optional functions, request circuits, and chain circuits. Included in the discussion of the operation of the IOC is the interaction between the IOC and CPU and the IOC and IOA.

**IOC Operation Description.**—The operation description of the IOC covers the following functions: CPU-IOC communication, IOC priority, I/O command execution, buffer mode transfers, buffer monitoring, and buffer mode termination. These functions will be discussed in the following paragraphs.

The IOC is the major unit of the computer set that controls the transfer of data between the main memory and various external devices. I/O operations are initiated by the CPU when it executes an initiate IOC (f = 07 4) instruction. The IOC accepts the instruction and sends an acknowledge to the CPU. The CPU is then free to return to other functions. The IOC operates independently to accomplish its I/O functions using a repertoire of IOC commands stored in computer main memory. The address of the first IOC command is contained in the 18-bit address field of the f = 07 4 instruction. The IOC also responds to an additional five CPU/IOC instructions that do not access main memory and that are executed entirely between the IOC and CPU.

The IOC scan priority circuits and request priority circuits examine both nonbuffered and buffered IOC requests before beginning execution of any IOC operation to determine the priority of each request in a particular class. Nonbuffered requests are generated by logic circuits within the computer: CPU, IOC RTC, IOC monitor clock, or chain commands. These requests do not establish buffer limits since no data is transferred either to or from the computer. Buffered requests, however, are generated to transfer data either to or from the computer and a peripheral device. These requests do establish buffer limits. The IOC alternates between buffered and nonbuffered operation. The IOC priority operates in a fixed mode. The request priority is reinstated at its highest priority state after a request is honored.

Upon receipt of the command address from the CPU, the IOC loads the 18-bit command address into the CAR associated with that CPU. If the chain bit of an IOC command is not set, the IOC executes a single command from the command repertoire. If the chain bit is set, the IOC executes an additional command. If the chain bit is set and an initiate buffer command (f = 10 = 13) is initiated, the IOC stores selected fields of the command word into a buffer control word (BCW) in control memory. The BCW is associated with the channel and function specified in the command word and enables an input or output transfer operation with a peripheral device. When the buffer operation specified by the I/O command is terminated, the IOC reads a new command address from the CAP in the BCW. Using the CAP, the IOC obtains the new I/O command from memory and executes it without attention from the CPU. The terminate buffer command (f = 14) disables the transfer conditions and terminates the buffer. The remaining 10 IOC commands perform housekeeping chores to support the initiate buffer commands and to load or store IOC control information in main memory.

After priority has been established for a channel, the IOC performs the general steps for a buffer input, output, external function, or external interrupt transfers as follows:

1. Read the control memory word from the assigned control memory location.
2. For input or external interrupt, store the word from the input data lines at the current address specified if it is a full word. If it is a half-word or quarter-word transfer, store the specified byte or bytes in the proper byte position(s) in the current address.
3. For output or external function, read the word from the current address and place the word or appropriate byte or bytes of the word on the output data lines.
4. Update the byte portion of the control memory word for quarter-word or half-word transfers. When this task is completed, increment

the control memory word current address portion by one. Terminate the buffer if the updated current address equals the final address. Initiate the first chained command if indicated.

5. Restore the updated control memory word address in the assigned memory location.

6. Set the input data acknowledge (IDA), output data acknowledge (ODA), external function acknowledge (EFA), or input acknowledge (external interrupt) line. These items are repeated for each request from the external device until transfer is terminated.

Buffer mode transfers are initiated with or without monitor under control of the IOC commands. When a buffer transfer with monitor terminates, an interrupt is generated at the CPU class III interrupt entrance address. When a buffer with monitor terminates for a channel-assigned intercomputer mode of operation, the monitor interrupt does not occur until the last word of the buffer has been acknowledged.

In either the normal buffer or ESI buffer modes of data transfer, the IOC transfers data words as directed by the control memory word, starting at the current address and continuing to the final address. The IOC compares the updated current address with the final address for each word transferred and increments the current address of the control memory word.

**Standard IOC Functions.**—The standard IOC functions are input data, output data, external interrupt, external function, external function with force, monitor mode, and chain mode. These functions will be discussed in the following paragraphs.

An *input data function* is performed by two sequences—an execute sequence and a buffer sequence. The execute sequence sets the active flip-flop for the selected I/O channel, transfers the control memory word for the input function to control memory, and stores the updated command address in control memory to form the CAP. Upon completion of the execute sequence, the buffer sequence is initiated by an input request. One data word is transferred per input request. The buffer sequence transfers the bca from control memory to the MMAR, gates the input data to the main memory locations indicated by the MMAR contents, compares the bfa to the bca of the control memory word, and issues an IDA signal following completion of the data transfer. Once initiated, an input data function can be terminated by executing a terminate buffer on $C_j$ command, K = 0 or when the bfa = bca.

*Output data functions* are processed the same as the input data functions, except for the following differences: The buffer sequence is initiated by an ODR. The output data function is terminated under program control by a terminate buffer on $C_j$ command, k = 1; and the data is transferred out of memory to the output data lines.

*External interrupt functions* are processed the same as input data, except the buffer sequence is initiated by an EIR, and the interrupt function is terminated under program control by a terminate buffer on $C_j$ command, k = 3.

*External functions* are processed the same as output data functions, except the buffer sequence is initiated by an EFR, and the external function (EF) is terminated under program control by a terminate buffer on $C_j$ command, k = 2.

An *external function with force* is processed the same as an external function except that no external function request (EFR) is needed to initiate the buffer sequence. An external function with force permits communication with external devices that have no provision for sending EFRs.

The *monitor mode* generates and transmits class III interrupts to the CPU to interrupt the computer program. The monitor mode is initiated after the termination of a buffer function, if the monitor bit of its control memory word is set. A particular monitor mode generates a corresponding IOC data monitor interrupt to the computer program. This interrupt transfers program control to the class III interrupt entrance address. The ISC determines the monitor entrance address selected.

The *chain mode* allows the IOC to operate independently of the CPU. It is a programmed mode that permits the IOC to address and request commands from main memory without executing continuous f = 07 4 CPU-IOC instructions. Chaining is indicated by the set state of the chain bit (bit 18) of an IOC command or by the set state of a chain active bit. If one of these bits is set, another IOC command is obtained from main memory and executed. The current IOC command may have been addressed from one of three command address registers (CARs) or by the CAP of a control memory word. During the execution sequence of an IOC command, the address in the CAR or CAP that addressed the current command is updated. The IOC chain continues as long as the chain bit in each successive command is set. If an IOC chain generates a request that causes an IOC memory interrupt, that chain terminates and an interrupt is sent to the CPU. Other active IOC chains continue to run. Take care when you use a CAR chain. If the CAR is kept active, the CPU will be prevented from initiating any further operation with the IOC. A CAP chain is the recommended method of chaining in the IOC.

**IOC Optional Functions.**—The IOC can perform the following optional functions: an externally specified address (ESA), externally specified index (ESI), and intercomputer. Any I/O channel can be modified for ESI, ESA, or intercomputer communication by way of the I/O mode selector. (These operations will not be covered here. They are similar to the operations performed by the Mk 152 computer.)

**IOC Request Circuits.**—The request circuits present input, output, external interrupt, and external function requests from the IOA to the IOC. These requests are continually presented to the IOC until honored by the priority circuits or until disabled by a program instruction. The request circuits consist of one-shot and priority circuits.

The *one-shot circuits* synchronize and gate input requests from the IOA. The one-shot circuit gates the input requests presented to the IOC. The sync flip-flop synchronizes the gate requests with IOC timing. A one-shot circuit gates a request only once. The output from the one-shot circuits enters the priority circuits for priority determination.

The *priority circuits* determine the order in which requests and interrupts are honored. The priority circuits consist of request and interrupt priority logic. The request priority logic consists of channel and function priority circuits. The *channel priority circuits* perform a priority determination of requests based on channel number and group number. The 16 channels are divided into four groups of four channels each. Priority is assigned to these channels, as shown in table 3-4, by the channel selection and group selection circuits. The *function priority circuits* determine the order of honoring requests when channel priority honors more than one request per channel. Table 3-5 shows function priority. The interrupt priority circuits determine the order in

Table 3-4.—Channel Priority Determination

| GROUP | CHANNEL | PRIORITY |
|---|---|---|
| 0 | 0 | LOWEST |
| | 1 | |
| | 2 | |
| | 3 | |
| 1 | 0 | |
| | 1 | |
| | 2 | |
| | 3 | |
| 2 | 0 | |
| | 1 | |
| | 2 | |
| | 3 | |
| 3 | 0 | |
| | 1 | |
| | 2 | |
| | 3 | HIGHEST |

Table 3-5.—Function Priority

| FUNCTION | PRIORITY |
|---|---|
| EXTERNAL INTERRUPT | HIGHEST |
| EXTERNAL FUNCTION | |
| OUTPUT DATA | |
| INPUT DATA | LOWEST |

which monitor interrupts are honored. Monitor priority circuits operate identically to the request priority circuits.

**IOC Chain Circuits.**—The chain circuits control the execution and priority evaluation of chain commands. A chain command allows the IOC to execute another I/O command upon the completion of the current operation. The chain circuits are composed of the chain register and the chain priority circuits.

The *chain registers* indicate the channels of a function performing a chain command following the termination of the current function buffer operation. The chain (c) bit must be set in the current function word. There are four types of chain registers: input, output, external function, and external interrupt. The 16-bit chain registers contain 1-bit per channel, and they are set and cleared under program control. The execution of an INITIATE BUFFER (f = 10 – 13) command or a SET CHAIN ACTIVE (f = 16) command sets the chain registers. Completion of the chain command clears the chain registers.

The *chain priority* logic determines the order in which chain commands are honored. Chain priority consists of channel and function priority. These circuits function identically to the request priority circuits.

### I/O Adapter (IOA)

The IOA consists of 16 input/output channels arranged in groups of four input and output channels. Each group of four I/O channels may be configured as either fast or slow parallel interface. The fast interface uses line logic levels of – 3.0 and 0 or + 3.5 and 0 volts, while the slow interface uses line logic levels of 0 and – 15 volts.

The parallel I/O adapter (fig. 3-21) transfers all data to and from the peripheral devices, 32 bits at a time. The parallel IOA is basically an interface unit between the computer IOC and the peripheral device. It is composed of the I/O control circuits, input data receivers, output register, and data (line) drivers.

**I/O CONTROL CIRCUITS.**—The I/O control circuits generate the enables and acknowledge signals required to transfer data into and out of the computer. The I/O control circuit is composed of the input control circuits, output control circuits, request circuits, and the command drivers.

The *input control circuits* (fig. 3-21) generate enables to gate the input data (32 bits) from the input data receivers to the IOC. The input control circuits also issue acknowledge signals that are fed to the command drivers. Control signals received from the IOC determine which input enables and acknowledge signals are to be activated.

The *output control circuits* (fig. 3-21) generate enables to gate data, received from the IOC, in the output register (32 bits) to external devices. The output control circuits also issue acknowledge signals for output functions. Control signals received from the IOC determine which output enables and acknowledge signals are to be activated.

In *request circuits*, the request receivers (fig. 3-21) transfer input, output, external function, and external interrupt requests from external devices to the IOC for priority determination. The request receivers convert incoming signals from line logic to computer logic.

The *command drivers* (fig. 3-21) issue acknowledge signals to external devices for input, output, and external functions. Acknowledge enables from the I/O control circuits gate the acknowledges from their command drivers. The command drivers also issue external interrupt enables to external devices for external interrupt functions. Control signals from the IOC gate the external interrupt enable signal from its command driver. The command drivers act as logic level converters, shifting the various commands from computer logic to line logic.

**INPUT DATA RECEIVERS.**—The input data receivers transfer data (32 bits) inputted from external devices to the IOC. Channel and group enables issued by the input control circuits gate the input data to the IOC. The input data receivers convert data from line logic to computer logic.

**OUTPUT REGISTER.**—The output register (fig. 3-21) transfers data (32 bits) held in the IOC to an external device. The output register enables, generated by the output control circuit, gate the data from the output register to the data drivers (line drivers).

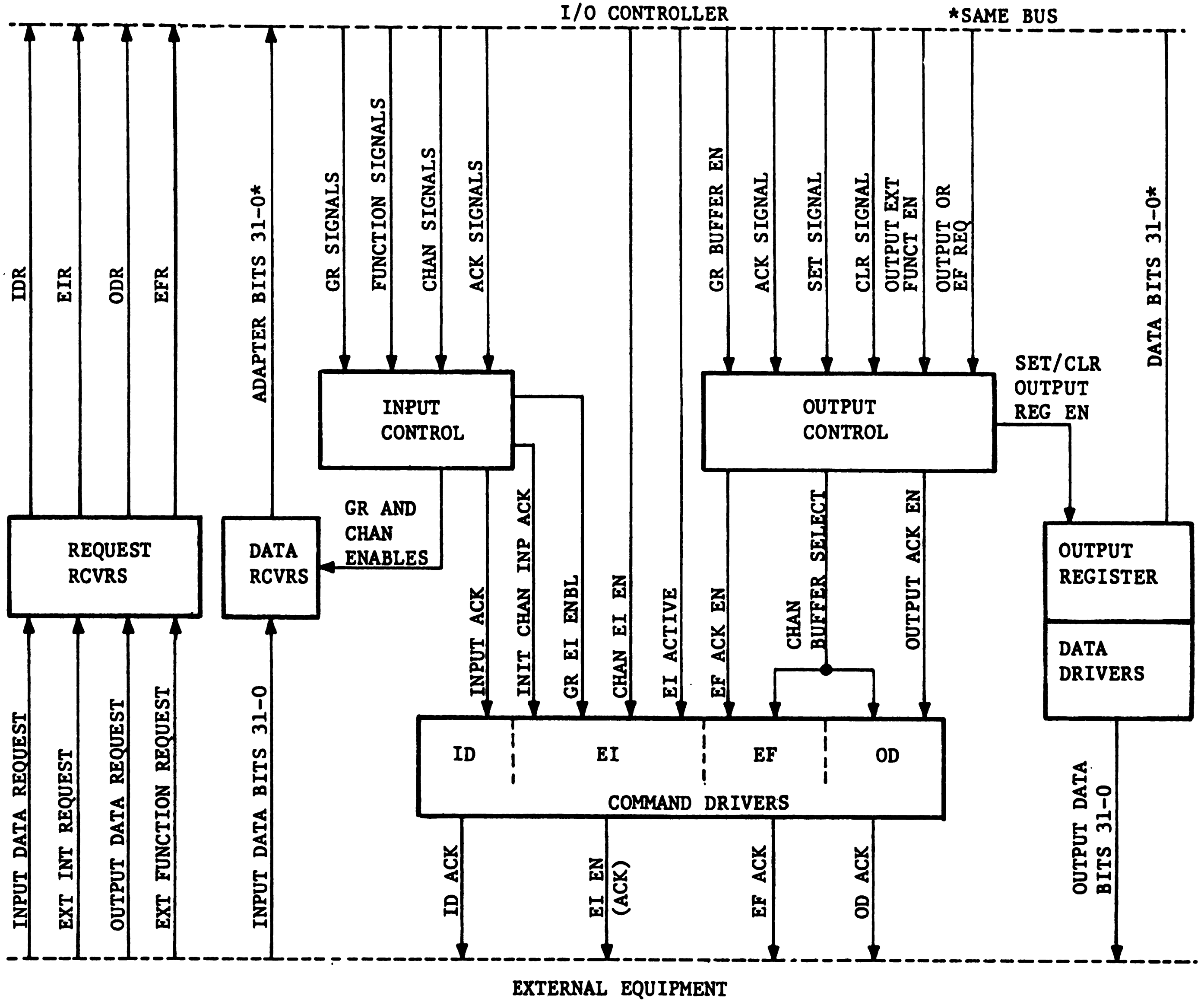


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Figure 3-21.—Parallel I/O adapter block diagram.

**OUTPUT DATA DRIVERS.**—The output data drivers (fig. 3-21) receive the data (32 bits) from the output register, convert it from computer logic to line logic, and transmit it to an external device.

### Core Memory

The primary function of the CMU is to store programs and data. The CPU and IOC communicate with the CMU through eight bidirectional memory busses. The memory bus serves as a bidirectional data path between the requestor and the CMU. Control lines for both the requestor and memory are included in the memory bus. The CMU communicates only with the CPU and IOC. The CMU can be broken down into three functional areas: control, timing, and address selection and data read/write. These sections are discussed in the following paragraphs.

**CONTROL CIRCUITS.**—The control circuits of the CMU consist of the following logic: channel selector, request and requestor-holding registers, priority evaluation, interface control, and byte control. These circuits provide for the control of requests by units external to the CMU, and translation of these requests.

**Channel Selector.**—The channel selector (fig. 3-22, a foldout at the end of this chapter) is a logic network that enables data words or address words to be gated into and out of the CMU by way of the eight bidirectional memory busses. The channel selector logic also gates data from the memory stacks into the CMU. Enables for the channel selector are provided to the channel selector by the interface control logic.

**Request and Requestor-Holding Registers.**—The request and requestor-holding registers (fig. 3-22) receive memory requests from the IOC and CPU modules. The channel request register sends this request to priority evaluation. The requestor-holding register returns a requestor hold signal to the requesting logic and holds the address until it is entered into the S register. At the same time the requestor's central processor or IOC is suspended until the requestor hold line is deactivated. Both the channel request register and the requestor-holding register are 8-bit registers.

**Priority Evaluation.**—The priority evaluation logic (fig. 3-22) receives request signals from the channel request register and sends a channel active signal to the interface control circuitry upon acceptance of the request. Priority also returns a lockout request to the request logic, preventing acceptance of another request until the current request has been fulfilled.

**Interface Control.**—The interface control logic (fig. 3-22) receives channel active signals from the priority evaluation logic. These signals enable the selected channel to receive read or write commands from the requesting unit (IOC or CPU). The interface control logic also enables the channel selector network to allow the activated channel data into the Z register. The interface control logic transmits a data-ready signal to the requestor logic when data has been retrieved from memory and set on the data bus lines for the requesting unit. The write-byte signals from the requestor logic is routed through the interface control logic to the byte control logic.

**Byte Control.**—The byte-control logic (fig. 3-22) receives selected write-byte signals from the interface control logic and generates the enables necessary to enter data into the Z register. The byte-control logic also generates the signals that disable the sense amplifiers for the word, half word, or quarter word in which data is to be written. Entry of data in bytes, instead of whole words, is designated by the byte control logic.

**TIMING.**—The timing circuits of the CMU (fig. 3-22) control memory timing after a read or write cycle has been initiated by priority evaluation. The timing circuitry controls the following functions:

- Clearing the Z register
- Gating data into the Z register during a read operation
- Entering the address into the S register
- Executing X and Y primary, secondary, and diode selection during a read or write operation

- Strobing memory address stacks 0-3
- Provides timing for the current regulators
- Clearing the request and requestor-holding registers
- Starting the read or write operation

The timing logic controls the initiation of the following functions simultaneously upon gating the selected word address into the S register for a read or write operation:

- Gating of the X and Y diode selectors
- X and Y secondary and primary selection

Upon initiation of either a read or write operation, the CMU performs a read cycle and then a write cycle.

**ADDRESS SELECTION AND DATA READ/WRITE OPERATION.**—The address selection and the data read/write operations consist of these steps:

1. Address translation
2. Read cycle
3. Write cycle

*Address translation* involves the transfer of the data word address from the Z register into the S register and translator. The S translator enables the various logic elements that provide selection of a unique address.

During a *read cycle*, data is read from the unique address selected and transferred to the Z register for transmission to the requesting unit (CPU or IOC).

During a *write cycle*, data is transferred from the Z register to the various write logic components and written into a unique address in the memory stack selected by address translation.

Some of the circuit elements associated with address selection and the read/write operation are explained in the following paragraphs.

**Z Register.**—The Z register (fig. 3-22) is a 32-bit register that receives the data and address from the requestor unit (IOC or CPU) by way of the channel selector logic. The incoming address is gated from the Z register into the S register by the channel-active signal from control. During a write operation, the Z register receives data words from the requestor and sends them to the inhibit selectors. From there the data word is stored in the memory stack selected. During a read operation, the Z register receives data words from the sense amplifiers and transmits them to the requestor by way of the data bus. The data word is also sent back to the inhibit selectors so that it can be written back into memory.

**S Register and Translators.**—The 15-bit S register and translators (fig. 3-22) receive the selected memory address from the Z register before a read or write operation. The translation circuitry associated with the S register then translates the various address bits into enables, which are transferred to the address selection circuits. Table 3-6 depicts the address word bit translation.

**X and Y R/W Diode Selectors.**—The X and Y R/W diode selectors (fig. 3-22) receive inputs from the S translator and timing. The S translator sets up the quadrant selection, and timing sends a "read 1" or "write 1" signal that gates the X and Y R/W diode selector to the X and Y drive line circuitry. The X and Y read and write

Table 3-6.—Address Word Bit Translation

| S REGISTER BITS | TRANSLATION |
|---|---|
| 1, 2, AND 0 OR 14 | X SECONDARY SELECTION 0-7 |
| 3, 12, AND 13 | X PRIMARY SELECTION 0-7 |
| 4 AND 5 | X DIODE SELECTION 0-3 |
| 6, 7, AND 8 | Y SECONDARY SELECTION 0-7 |
| 9, 12, AND 13 | Y PRIMARY SELECTION 0-7 |
| 10 AND 11 | Y DIODE SELECTION 0-3 |
| 12 AND 13 | STACK SELECTION 0-3 |
| 11, 12, AND 13 | INHIBIT HALF STACK UPPER OR LOWER |

selectors are not enabled at the same time. They are controlled by timing and are enabled later in the timing sequence. A read cycle is always initiated first, and a write cycle follows. The drive current regulators input to the X and Y R/W diode selectors. The drive current regulators limit the X and Y drive current. The diode selectors enable the X and Y read drive line or X and Y write drive line for one of the four quadrants in all four of the memory stacks.

**X and Y Primary Selectors and Drive Transformers.**—The X and Y primary selectors and drive transformers (fig. 3-22) receive inputs from the X and Y secondary selectors, S translator, X and Y R/W diode selector, and timing. The S translator circuits enable one each of the X and Y primary selectors, the X and Y secondary selectors enable one of the secondary windings on each of the eight X and Y drive transformers. The X and Y diode selector inputs are received from the primary side of the read or write current regulators. The read or write driver enables one of two separate primary windings on the drive transformer and induces current flow in one direction during a read cycle and the opposite direction during a write cycle. The "read 1" or "write 1" signal from timing completes selection for the X and Y read-write diodes, X and Y secondary selectors, and X and Y primary selectors and drive transformers. Enabling all three circuits and turning on the current regulators allow the read or write cycle to be performed.

**X and Y Secondary Selectors.**—The X and Y secondary selectors (fig. 3-22) receive inputs from the S translator and the timing circuitry. The S translator develops enables for both the X and Y secondary selectors, which enables the selection of one of the secondary windings for each of the eight X and Y drive transformers. There are eight X and eight Y drive transformers, and each drive transformer has eight secondary windings. Of these eight secondary windings, the secondary selector circuits enable the same winding for all eight drive transformers. The enables are produced under the control of the "read 1" or "write 1" timing signals.

**Inhibit Selectors.**—The inhibit selectors (fig. 3-22) receive enable signals from the S translator logic. The S translator develops an enable for one-half stack (*upper* or *lower*) in memory stacks 0-3. The terms upper and lower refer to the upper or lower half of the addresses contained in any one memory stack. For memory stack 0, the lower-half addresses are $0000_8$ through $3777_8$, and the upper-half addresses are $4000_8$ through $7777_8$. The inhibit selectors feed through each memory stack, and the circuit is completed by the inhibit current regulators. The inhibit selectors are activated only when writing zeros.

**Drive Current Regulators.**—The drive current regulators (fig. 3-22) receive inputs from the S translator, timing, and temperature sensors contained within each memory stack. The temperature sensors in each memory stack detect an increase or decrease in temperature within the stack. The temperature sensor circuit of each stack feeds a varying control signal to the reference voltage regulator where it is used to vary the reference voltage with the temperature of the memory stacks. The reference voltage regulator, in turn, supplies the voltage to the drive current regulators. The varying reference voltage increases or decreases the drive current with a corresponding decrease or increase in stack temperature.

**Inhibit Current Regulators.**—The inhibit current regulators (fig. 3-22) gate the inhibit pulse on the inhibit line of the memory stack. The inhibit regulators receive an enable from the Z register, and they are activated by a timing signal. Inhibit current regulators are enabled only during a write cycle when there is a "0" in the corresponding bit of the Z register. The inhibit timing signal activates the inhibit regulator. The resulting inhibit current pulse prevents a "1" from being written into the associated bit position at the address selected. The reference voltage, received from the drive current regulators, controls the amplitude of the inhibit drive current pulse.

**Sense Amplifiers.**—The sense amplifiers (fig. 3-22) read the state of the cores selected during a read operation. The sense amplifiers receive inputs from the memory stack, timing, and byte control. The byte control logic disables the sense amplifiers during a write cycle and enables the sense amplifier strobe during a read cycle. The strobe signal from timing is coincident with a read condition in the sense amplifier. Data read by the sense amplifiers is transferred into the Z register.

**Memory Stacks.**—There are four memory stacks in each CMU chassis. The memory stack consists of a temperature sensor, X and Y drive lines, inhibit lines, sense lines, and magnetic cores. Each memory stack is capable of retaining 4,096 32-bit words. For a detailed explanation on the theory of operation of magnetic core memories, refer to the chapter on data storage devices in *Digital Computer Basics*, NAVEDTRA 10088.

### Double-Density Mated Film Memory

The double-density mated film memory (DDMFM) unit of the AN/UYK-7(V) computer set provides 32,768 32-bit words of random access memory (RAM) and has the same function as the CMU. The memory operation is asynchronous on a request/acknowledge basis by way of eight bidirectional data busses. Response to requests presented to memory is on a priority basis, determined by the priority logic. The DDMFM is composed of four functional sections: front-end circuits, memory timing, access circuitry, and sense circuitry.

**FRONT-END CIRCUITS.**—The front-end circuits provide control of the data flow to and from the DDMFM. These logic circuits consist of priority processing, lower channel active, upper channel active, byte control, address storage, and data storage circuits. These logic circuits are discussed in the following paragraphs.

**Priority Processing.**—The priority processing logic circuits (fig. 3-23) receive and store requests from each channel and store the read/write commands for the channel granted priority by the lower channel logic. The priority processing logic activates the REQUESTOR HOLD signals when the request flip-flops set and deactivate the REQUESTOR HOLD signals when the read or write command flip-flop is set. The priority processing circuitry also controls the presentation of requests to the lower channel active and upper channel active logic and gates in the address for the channel selected by the lower channel active logic.

**Lower Channel Active.**—The lower channel active (LCA) logic (fig. 3-23) selects the channel with the highest priority for those channels that have request flip-flops set in the priority processing logic. The LCA logic generates a lockout to prevent new requests from being set in the request flip-flops during the channel selection time and initiates a first section memory timing cycle. The address present on the data/address bus is gated into the channel address register by the LCA logic during the channel selection time. A flag bit is also set in the address register along with the address word if the write command is active for the channel. The read and write commands are also stored in the priority processing logic during the LCA channel selection time.

**Upper Channel Active.**—The upper channel active (UCA) logic (fig. 3-23) selects the channel with the highest priority and initiates a memory cycle to perform the specified operation (read or write). The UCA logic makes the contents of the selected channel's address register available for translation, and it selects the channel's data register for write data during a write operation. The UCA logic also enables the selected channel's data transmitters during a read operation.

**Byte Control.**—The byte control logic (fig. 3-23) stores the byte designation for the current data word to be written into memory. The write bytes are stored in flip-flops for each channel by way of a byte enable flip-flop, which is set when the channel write flip-flop is set. The byte enable flip-flop is cleared by deactivation of the channel write command. Clearing the channel's write command and setting the channel's write flip-flop notifies the UCA logic to initiate a write cycle for the channel. The write bytes (a total of four—one for each 8-bit data byte) set the write data word (present at the selected channel) into the channel data register when the byte enable flip-flop is set. The byte flip-flops, when set, disable the internal memory data strobe and enable the transfer of data from the channel data register to the internal memory data register.

**Address Storage.**—The address storage logic (fig. 3-23) contains eight 16-bit address storage registers, one for each channel. The lower 15 bits of the address storage register contain the address

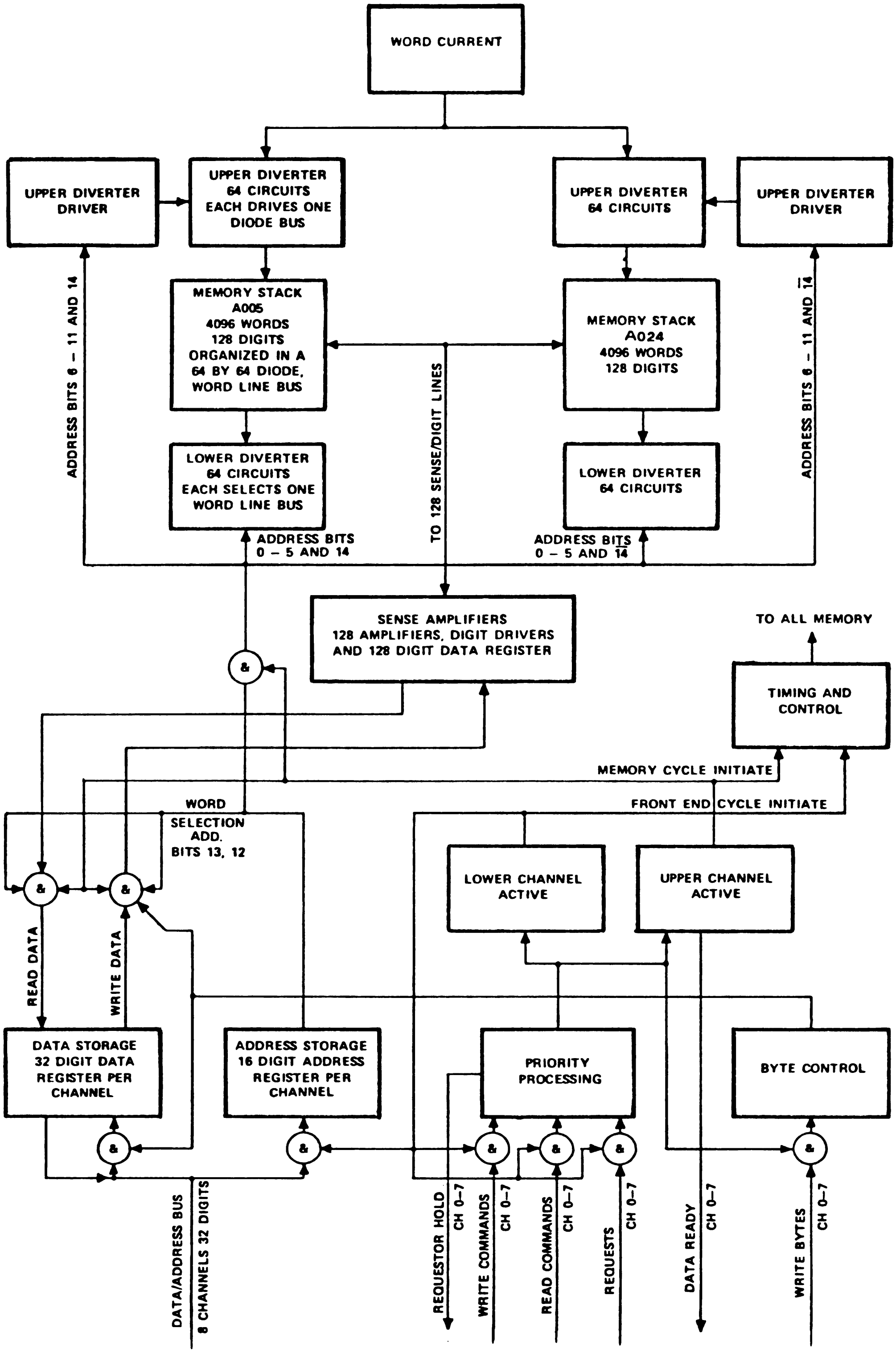
WORD CURRENT
UPPER DIVERTER DRIVER
UPPER DIVERTER 64 CIRCUITS EACH DRIVES ONE DIODE BUS
UPPER DIVERTER 64 CIRCUITS
UPPER DIVERTER DRIVER
MEMORY STACK A005 4096 WORDS 128 DIGITS ORGANIZED IN A 64 BY 64 DIODE, WORD LINE BUS
MEMORY STACK A024 4096 WORDS 128 DIGITS
LOWER DIVERTER 64 CIRCUITS EACH SELECTS ONE WORD LINE BUS
LOWER DIVERTER 64 CIRCUITS
ADDRESS BITS 6 – 11 AND 14
ADDRESS BITS 6 – 11 AND 14
TO 128 SENSE/DIGIT LINES
ADDRESS BITS 0 – 5 AND 14
ADDRESS BITS 0 – 5 AND 14
SENSE AMPLIFIERS 128 AMPLIFIERS, DIGIT DRIVERS AND 128 DIGIT DATA REGISTER
TO ALL MEMORY
TIMING AND CONTROL
MEMORY CYCLE INITIATE
FRONT END CYCLE INITIATE
WORD SELECTION ADD. BITS 13, 12
LOWER CHANNEL ACTIVE
UPPER CHANNEL ACTIVE
READ DATA
WRITE DATA
DATA STORAGE 32 DIGIT DATA REGISTER PER CHANNEL
ADDRESS STORAGE 16 DIGIT ADDRESS REGISTER PER CHANNEL
PRIORITY PROCESSING
BYTE CONTROL
&
DATA/ADDRESS BUS
8 CHANNELS 32 DIGITS
REQUESTOR HOLD
CH 0–7
WRITE COMMANDS
CH 0–7
READ COMMANDS
CH 0–7
REQUESTS
CH 0–7
DATA READY
CH 0–7
WRITE BYTES
CH 0–7

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Figure 3-23.—Double-density mated film memory block diagram.

to be read or written into. The 16th bit, the flag bit, is set if the write command for the channel is active at the time the address is stored. The address storage logic also contains circuitry for comparing the address at the channel selected by the LCA signal with the contents of the other seven channel address registers. When a flag bit is set in an address register and the selected channel's address is the same as that of the register in which the flag bit is set, a compare signal is generated. The compare signal sets a compare flip-flop for the selected channel. This establishes a request lockout and prevents a memory cycle for the channel whose address compared to the channel with a flag bit stored. The address register is cleared when a memory cycle is completed for the accessing channel.

**Data Storage.**—The data storage logic (fig. 3-23) contains eight 32-bit data storage registers, one for each channel. The data storage register stores write data for each of the eight data channels. The number of bytes used in the data storage registers is controlled by the channel's write byte signals. The data storage logic also contains the data transmitters used to transmit data from a memory reference to each channel data bus.

**MEMORY TIMING.**—The memory timing section of the DDMFM provides the enables, strobes, and set and clear signals for controlling the memory and priority processing cycles. Memory timing is initiated by the LCA and UCA logic. When a memory timing cycle is initiated by the LCA logic, only a priority processing cycle (front end) occurs. The priority processing cycle stores the address, read and write commands, and does an address compare for the channel selected by the LCA logic. If memory timing is initiated by the UCA logic, a memory cycle occurs. During the first part of the memory cycle, a priority processing cycle occurs if any request flip-flops are set. A memory cycle performs a read or write operation dependent on whether the read or write flip-flop is set for the particular channel. If both the read and write flip-flops are set (replace operation), two memory cycles are performed. Memory timing consists of the main delay line, strobe delay line, and timing flip-flops. These circuits are discussed in the following paragraphs.

**Main Delay Line.**—The main delay line provides all basic timing signals for setting and clearing of the flip-flops in the DDMFM circuitry. The main delay line consists of two sections. The first section of the main delay line provides timing for a priority processing cycle. Timing is terminated after the first section if memory timing is initiated by the LCA logic. If memory timing is initiated by the UCA logic, timing is allowed to proceed from the first section of the delay line into and down the second section for a memory cycle.

**Strobe Delay Line.**—The strobe delay line provides two timing pulses for the control of the sense amplifiers and one timing pulse for control of the word current generator. The timing pulses for control of the sense amplifiers are the DATA LATCH and CAPACITOR RESTORE signals. Both signals occur in four time increments, dependent on address bits 10 and 11 to compensate for the sense line delay.

**Timing Flip-Flops.**—The timing flip-flops provide the various width enable pulses for controlling the memory cycle.

**ACCESS CIRCUITRY.**—The access circuitry consists of the necessary logic circuits required to select and drive a word current pulse down a word line. The DDMFM is a word-oriented memory. This means that all memory elements that are read-out to provide a data word are intersected by one drive line, which provides the readout pulse. Readout occurs during the rise time (leading edge) of the word current pulse. Writing or restoration (after a read) of the memory elements occurs during the fall time (trailing edge) of the word current pulse and concurrent with a digit current pulse for each bit of the word. The direction of the digit current pulse determines the writing of a "1" or a "0." The digit current pulses are conducted down the sense lines. For a detailed explanation on the theory of operation of thin film memories, refer to the chapter titled "Data Storage Devices" in *Digital Computer Basics*, NAVEDTRA 10088. Address translation is performed by the upper and lower diverters.

The access circuitry consists of the word current generator, upper diverters, upper diverter drivers, lower diverters, and the memory stack diode bus-word line matrix. These are described in the following paragraphs.

**Word Current Generator.**—The word current generator (fig. 2-23) produces a controlled rise-time/fall-time current pulse that provides the switching field for memory elements. The word current generator also produces the drive pulse for the strobe delay line.

**Upper Diverter Driver.**—The upper diverter driver (fig. 3-23) translates address bits 6-11 to select one of 64 upper diverters required to divert the word current pulse to a diode bus in the selected memory stack.

**Upper Diverter.**—The upper diverter (fig. 3-23) diverts the word current pulse to a diode bus in the selected memory stack. Each of the two memory stacks has its own upper and lower diverters.

**Lower Diverter.**—The lower diverters (fig. 3-23) translate address bits 0-5 to select one of the lower diverters, which grounds a bus of 64-word lines to complete the word current path through the memory stack. Address bit 14 completes the word line selection by determining which memory stack has its diverters enabled.

**Memory Stack.**—The memory stack (fig. 3-23) contains 64 diode busses, each containing 64 diodes with common anodes. Each cathode of the 4,096 diodes is connected to a word line. The word lines are bussed in groups of 64. Each word line intersects 128 memory elements. Therefore, the internal memory word is composed of four data words. The memory elements and sense lines are deposited on glass substrates, each having 2,048 memory elements. The sense lines of two substrates are connected to provide one-half of a sense line bridge for one of 128 sense lines. The memory stack has a capacity of 4,096 128-bit words.

**SENSE CIRCUITRY.**—The sense circuitry amplifies and stores the memory element signal in a data register for transmission of the data word and restoration of the memory elements. The sense system provides the digit current pulses, the polarity of which determines whether ones or zeros are stored in the memory elements. The sense system is composed of a sense amplifier, data flip-flop, and digit driver for each of the 128 bits of the internal data word. Address bits 12 and 13 determine which group of 32 bits is transmitted as the data word or changed by a memory write cycle.

**Sense Amplifiers.**—The sense amplifier (fig. 3-23) is made up of a differential preamplifier coupled into a four-channel amplifier. The sense amplifier reads the data that is contained in the memory element. A sense line in each stack makes up one half of a sense line bridge connected into the preamplifier, with the channel select signal controlling the channel that is enabled. The polarity of the channel select signal is determined by address bits 6, 7, and 14, and it is used to define which polarity of the memory signal is a logic 1 or 0 for the selected address.

**Data Register.**—The data register (fig. 3-23) is composed of 128 flip-flops. During a memory read cycle, the outputs of the sense amplifiers are strobed into the data register. Address bits 12 and 13 determine which group of 32 bits is transmitted as the data word. During a memory write cycle, the strobe pulse is inhibited for the active write bytes in the 32-bit word determined by address bits 12 and 13. Address bits 12 and 13 determine which 32 bits of the data register are written into memory.

**Digit Drivers.**—The digit drivers (fig. 3-23) supply the drive pulses required to write data during the write portion of a memory cycle. There are 128 digit drivers, one for each bit in a memory word. Inputs to the drivers are supplied by gates on the outputs of the data register flip-flops. When these gates are enabled by a timing pulse from timing, the digit drivers generate drive pulses that write a logic 1 or logic 0 in the address's bit location, depending upon the contents of the data register.

**I/O Memory Bus.**—The I/O memory bus feeding the DDMFM contains the same control and data lines as for core memory; however, the

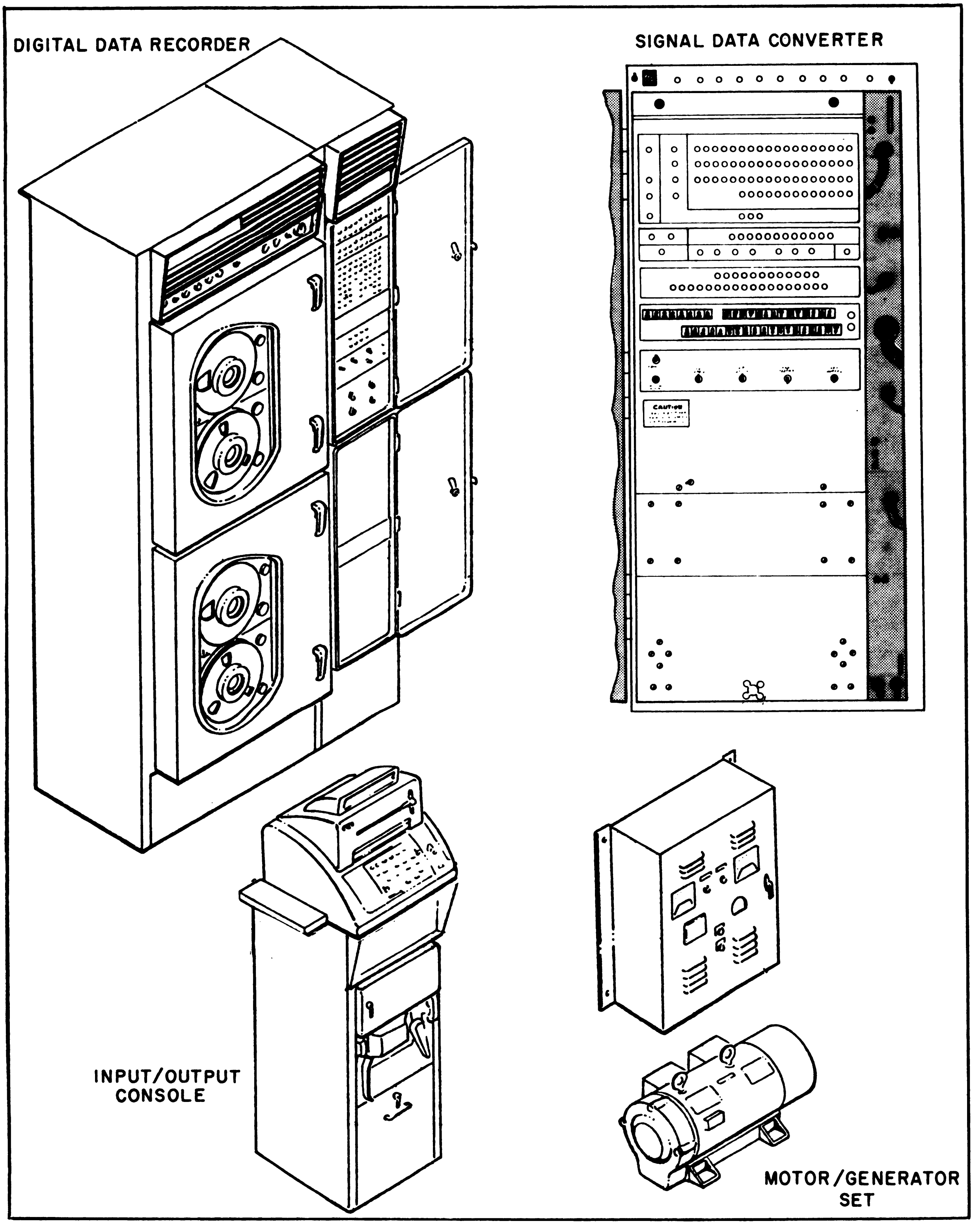

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Figure 3-24.—Computer complex peripheral equipment.

special P* bits 0 and 14 control signals are not used in the DDMFM. As with core memory, the address is selected by an 18-bit address word. The upper 3 bits of the address word (17, 16, and 15) are the memory unit address bits. These bits are decoded in the requesting unit (CPU or IOC) to request one of the eight DDMFM units.

## PERIPHERAL EQUIPMENT

Peripheral equipment includes the auxiliary or ancillary equipment that aids the computer in performing its function in the fire control system. The computer, along with the peripheral equipment, is often referred to as the computer complex. Peripheral equipment comprising a typical computer complex is shown in figure 3-24. A block diagram of a typical computer complex is shown in figure 3-25. A brief description of the peripheral equipment comprising the computer complex follows.

## INPUT/OUTPUT CONSOLE

The I/O console is used primarily to load data into the computer through a keyboard or a tape reader and to monitor data outputs from the computer with a tape punch or printer. A simplified block diagram of the I/O console is shown in figure 3-26.

### Logic Control

The control section contains circuitry that enables the console to communicate with the computer. It communicates with the computer on a request/acknowledge basis (recall *FC3*, NAVEDTRA 10276, chapter 6). The control section decodes the external function word from the computer to determine what function is to be performed. It generates enabling signals that energize and control the operation of the selected device. For example, if an output function is to be performed, it can enable either/or both the tape punch and/or printer. If an input function is to be performed, it can enable either the tape reader or the keyboard.

### Tape Punch

The tape punch is an electromechanical apparatus that punches information on paper

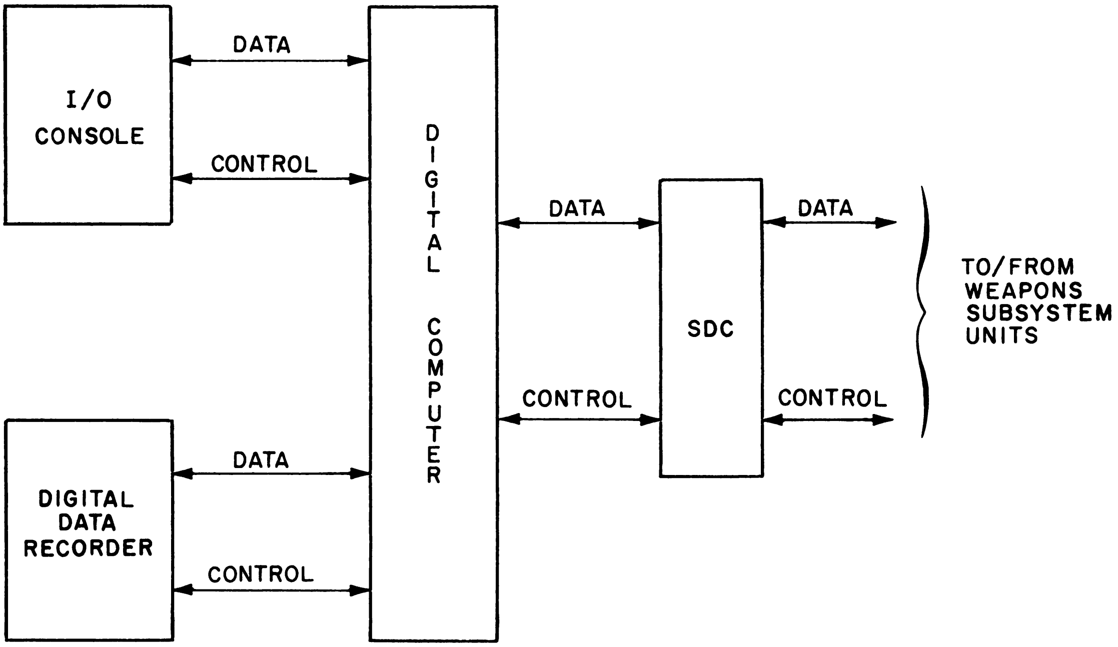

Figure 3-25.—Computer complex simplified block diagram.

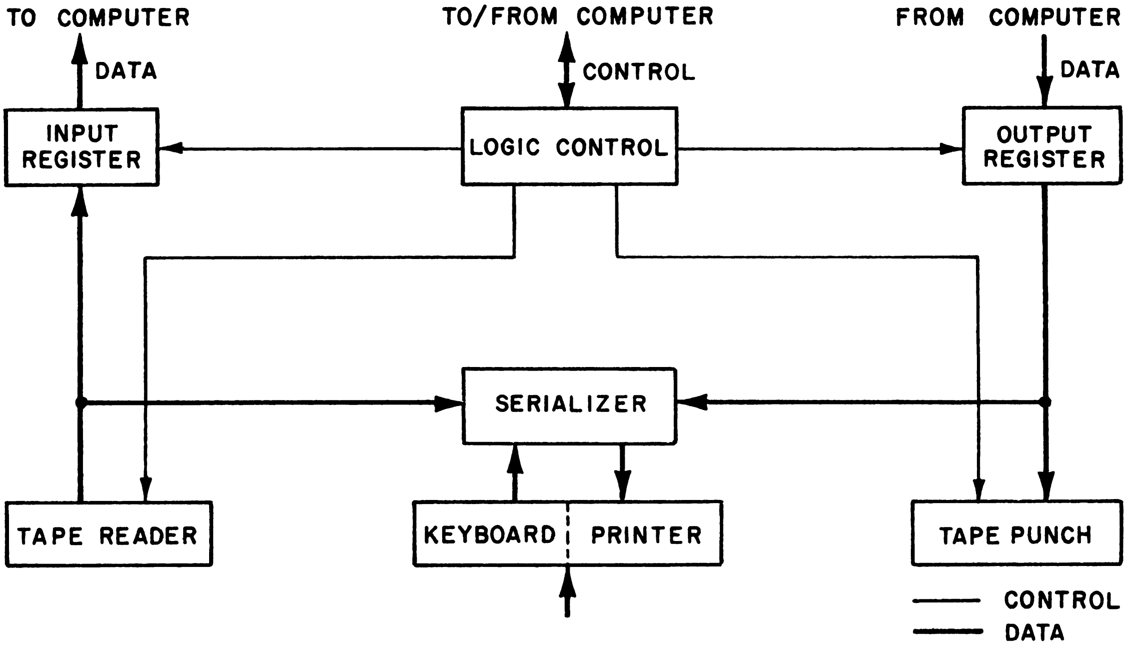

**Figure 3-26.—I/O console simplified function block diagram.**

tape. Information is received from the computer by way of the output register as combinations of electrical code pulses. Code pulses that enter the tape punch as electrical impulses are translated into mechanical motions that punch corresponding combinations of code holes in the tape. The code pulses are accompanied by a feed pulse, which causes the equipment to advance the tape.

### Tape Reader

The tape reader is a solid state, photoelectric, punched-tape reader that converts information on punched tape into dc signal levels. Pinch rollers in the tape-drive system pulls the tape in one direction across the face of a photodiode assembly. A hole condition in a given channel of the tape permits the passage of light from an exciter lamp to the photodiode for that given channel. The photodiodes are biased so that during a no-hole condition, the output is at a positive level, and during a hole condition, the output is at a negative level. The output from each photodiode is amplified and gated to the computer through the input register.

### Keyboard-Printer

The keyboard-printer is an electromechanical device that provides a means for transmitting and receiving information to and from the computer. Basically the keyboard-printer consists of a keyboard base, a printing unit, and a motor unit. The keyboard base converts mechanical actions into electrical signals; whereas the printing unit converts electrical signals into mechanical actions.

For each keyboard entry there is a chain reaction of mechanical motion that is converted into a unique string of electrical pulses for each graphic or function selected. These electrical pulses are applied to the serializer and to the printer. The printer uses a selection mechanism that converts the pulses into mechanical actions to position a complement of code bars. The resulting mechanical action either causes a character to be printed or a function to be performed, such as line feed or carriage return.

### Serializer

Data transmission to and from the keyboard-printer is done in a serial format using the

American Standard Code for Information Interchange (ASCII). (It might be beneficial for you to review *FC3*, NAVEDTRA 10276, chapter 6, for a refresher on serial data transmission.)

The serializer converts parallel data from the output register to the proper serial format and applies it to the printer. It also converts serial data from the keyboard to parallel data and applies it to the input register.

## DIGITAL DATA RECORDER (DDR)

The DDR is a large capacity, medium-speed, magnetic tape storage system. The basic unit consists of two tape transports and a control section. It is capable of receiving data from the computer and recording the data on magnetic tape and retrieving data previously recorded on tape and transferring the data to the computer. The DDR can be divided into five subsections as shown in figure 3-27.

### Primary Control Subsection

The primary control subsection consists of the circuits that exercise basic control over the other subsections. This section contains a master clock that provides basic timing pulses, which are used throughout the unit to sequence the operational functions. This subsection also contains function code translation circuitry that stores and decodes the portion of the external function command (from the computer) that is required while performing a specified operation.

### Input/Output Subsection

The I/O subsection is used to exchange data with the computer. It contains a communication (C) register through which all data (to or from the computer) passes. Duplex control circuitry within this subsection enables the DDR to be controlled by either of two computers on a one-at-a-time basis. It provides for requesting control, demanding control, releasing control, and master clearing of the DDR by the controlling computer.

### Data Format Subsection

The data format subsection is used during a write mode to disassemble computer words, develop parity, and to control the character (octal or bioctal) that is recorded on tape. In a read mode, the data format subsection receives data from the tape transport, checks and deletes the parity bits, assembles the data into computer words, and makes the data available for transmission to the computer.

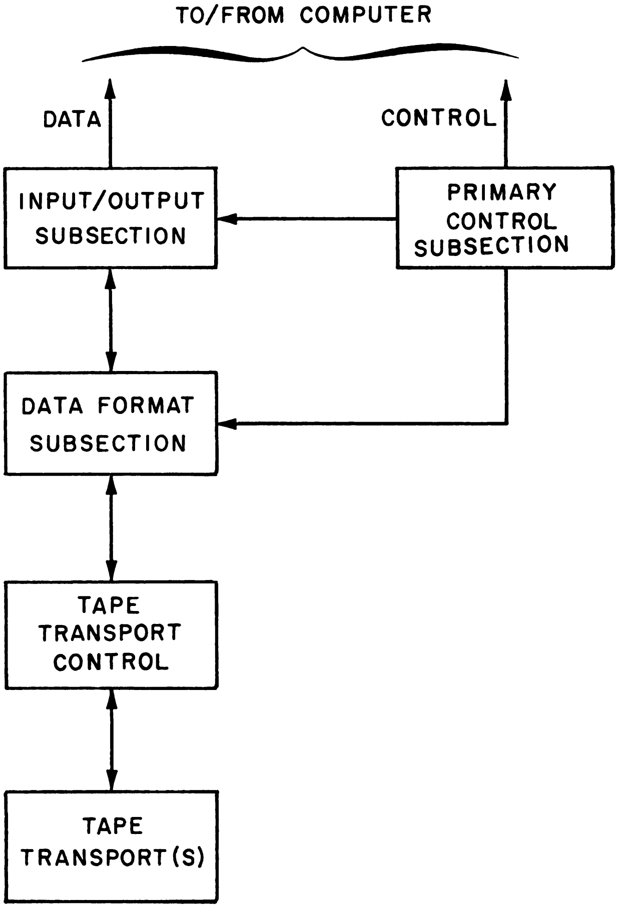

**Figure 3-27.—Digital data recorder simplified block diagram.**

### Tape Transport Control Subsection(s)

Each tape transport control subsection exercises direct control over the associated tape transport. Tape transport control performs the tape motion requirement of the function translation received from the F register and sends the appropriate command(s) to the tape transport. Some of the commands generated are STOP, go FAST, go REV, and go FWD. This section also contains the read and write amplifiers that amplify the data going to and from the read/write head in the transport.

### Tape Transport(s)

The tape transport contains the READ/WRITE head, the reel motor and servo system, the capstan motor and speed control, and associated circuits that move the tape in the correct direction. The transport heads write magnetically on the tape and read previously recorded data from the tape.

## SIGNAL DATA CONVERTER (SDC)

In a typical fire control application, the fire control computer is required to communicate with many external equipments. As you know, digital-to-analog and analog-to-digital conversion of data to and from the computer is the rule rather than the exception. It would be impractical to have a separate digital-to-analog/analog-to-digital converter for each equipment connected to the computer. To circumvent this problem, all of the would-be-needed converters are combined into one centralized unit—the SDC (fig. 3-28).

The SDC performs all of the conversions and data transfer required to permit communication between the computer and other units of the FCS. The SDC handles hundreds of input and output signals. It handles analog signals one at a time and digital signals 30 bits at a time, in a sequence and at a data rate commanded by the computer.

Each piece of equipment connected to the SDC is assigned a specific channel number. To receive data from a particular equipment, the computer sends the channel number of that equipment to the SDC, where the data on that channel is routed from the appropriate conversion circuitry within the SDC (that is, synchro-to-digital, ac-to-digital, digital-to-digital, and so forth). The converted data, at the proper time, is transferred to the computer. Data transfer from the computer to external equipment is performed in a similar manner.

## MOTOR/GENERATOR (MG) SET

The MG SET converts 220- or 440-Vac 60-hz 3-phase ships power to 115-Vac 400-hz 3-phase

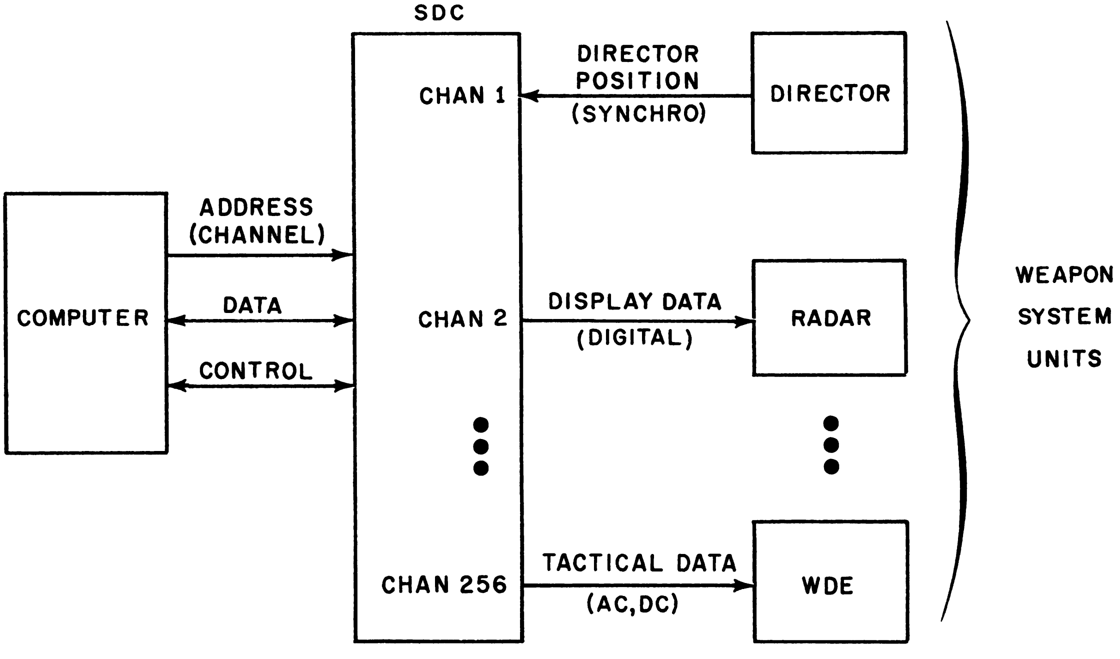

Figure 3-28.—SDC operation, simplified block digram.

power to operate the various equipments comprising the computer complex. The MG SET consists of two units (fig. 3-29)—an integral motor and generator assembly and a motor generator controller. The motor generator assembly consists of a 3-phase induction motor, a generator, and an exciter, all direct coupled by a common rotating shaft. The controller is enclosed in a cabinet and connected to the motor generator by cables. The following paragraphs contain a brief description of the MG SET.

### Motor

Three-phase input power is applied to the motor stator windings, where a rotating magnetic field is produced by current flow in these windings. The rotating magnetic field of the stator cuts the rotor windings to induce a circulating current in the rotor windings. The rotor current produces a magnetic field, which interacts with the stator field to produce the driving torque that turns the motor.

### Generator

The rotating rotor of the motor turns the generator rotor, which is mounted on the common shaft. Direct current from the exciter in the generator rotor produces a magnetic field that rotates with the rotor. As it rotates, the rotor field cuts stator windings and induces current into these windings. This current is the generator output and is delivered to the load through the controller.

### Exciter

The exciter is a current-generating device that supplies direct current to the generator rotor for field excitation. The direct current from the exciter is produced by a rotating rectifier assembly mounted on the exciter armature.

### Motor Control

The motor control circuits control the input power to the motor. It consists of a starter relay for start and stopping the motor. The motor control also contains provisions for removing the input power in the event the output from the generator exceeds or goes below certain levels.

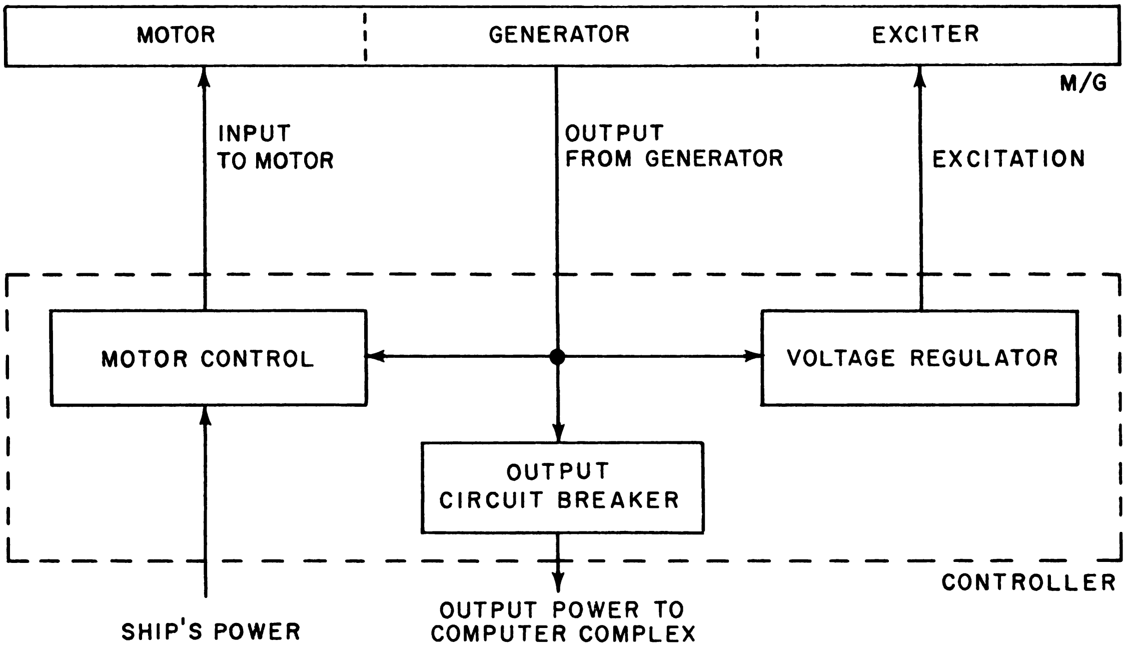

Figure 3-29.—M/G set simplified diagram.

### Voltage Regulator

The voltage regulator circuit maintains generator output voltage at 115 Vac within a certain percentage range. To do this, the voltage regulator senses a change in the generator output voltage and inversely changes exciter excitation current to produce the needed correction in generator output.

## SUMMARY

In this chapter, you were introduced to the two digital computers most commonly employed in shipboard fire control applications—the Mk 152 and the AN/UYK-7 digital computers. The discussion of the Mk 152 computer was presented first. It has the characteristics of a *basic* digital computer and is suitable as a foundation upon which we build our knowledge of the more advanced AN/UYK-7.

Making a comparison between the Mk 152 and the UYK-7, you should have noticed the similarities, as well as several major differences, between them. Some of the differences are in the AN/UYK-7 employing a CPU, a bussed communication system, and an I/O controller. These and other advances make the AN/UYK-7 a more powerful computer (in terms of data storage, instruction flexibility, and data processing speed) than the Mk 152.

A good understanding of the Mk 152 and AN/UYK-7 should provide you with the basic knowledge to understand other computers and prepare you to handle future advancements in computers and related digital equipment.

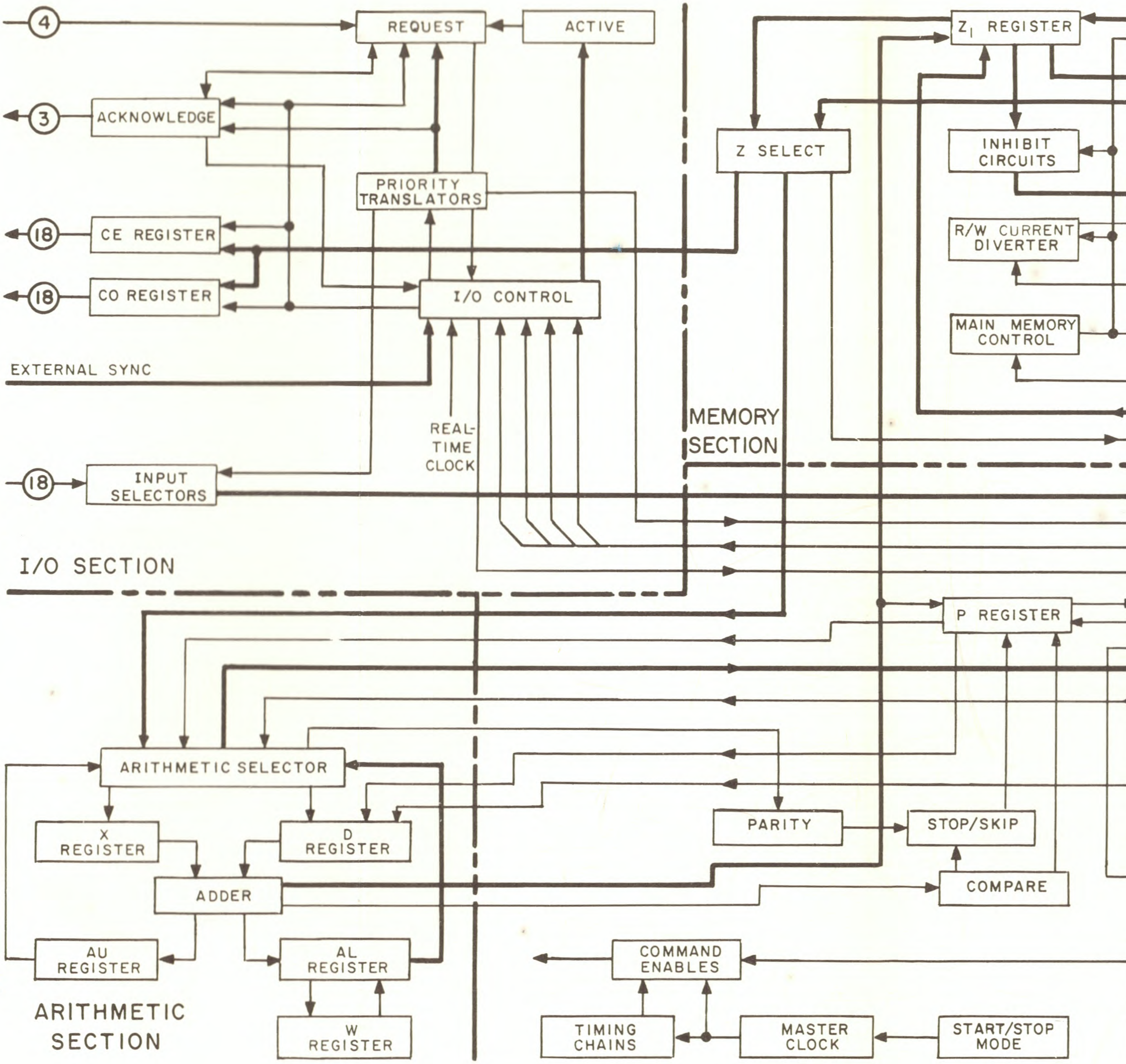

Figure 3-6.—Computer block diagram.

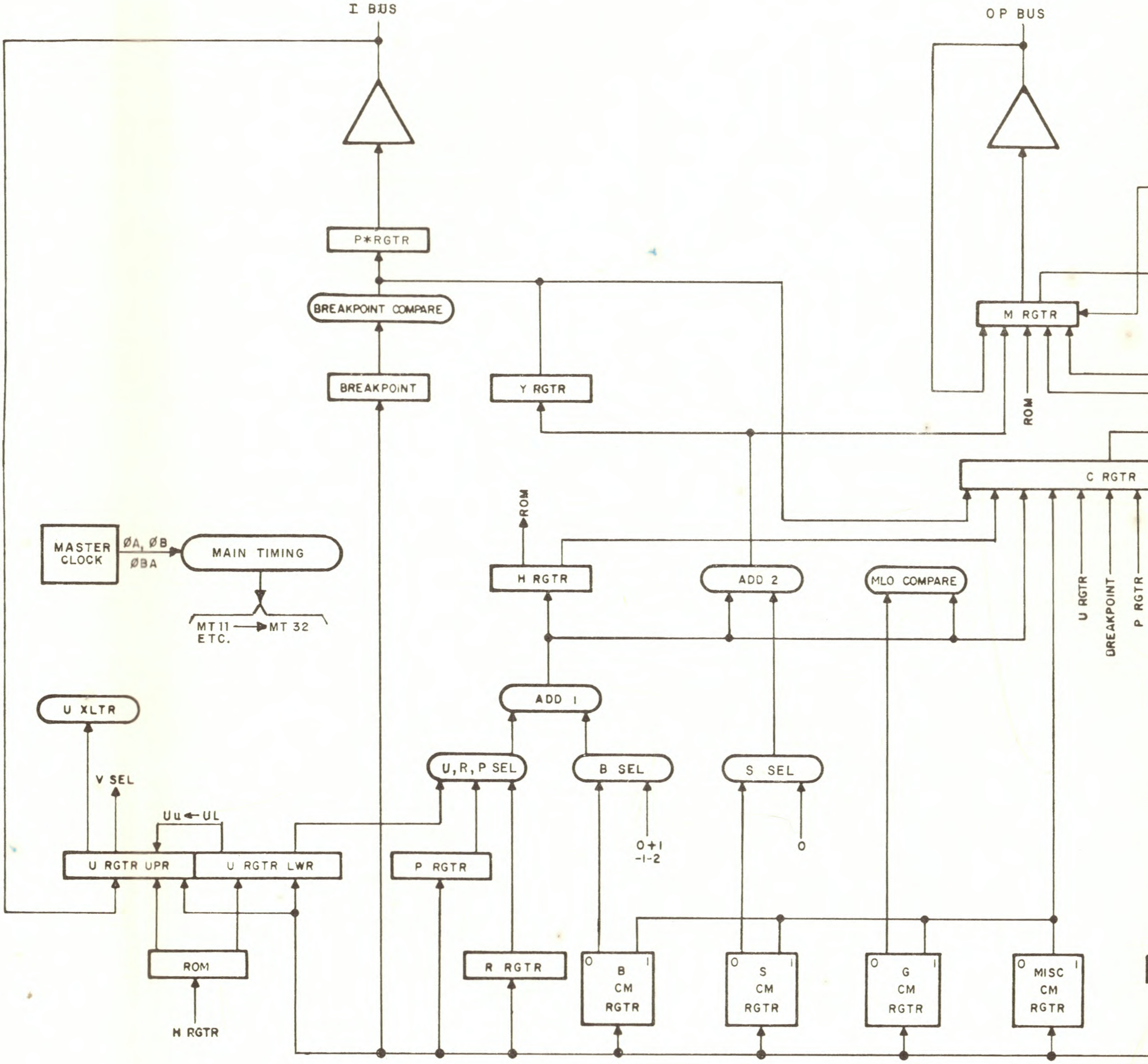

**Figure 3-17.—Central processor unit**

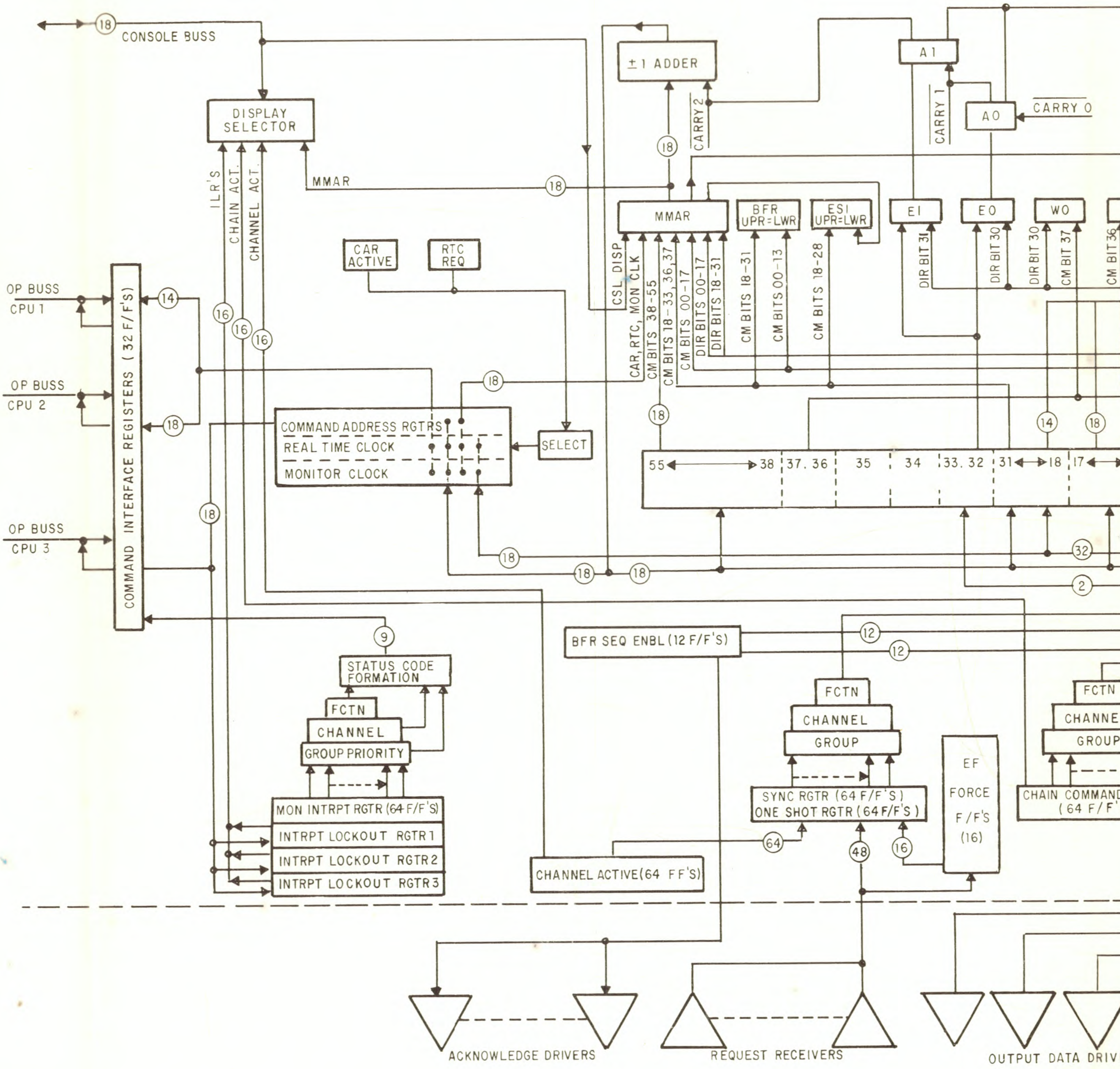

Figure 3-20.—I/O controller bloc

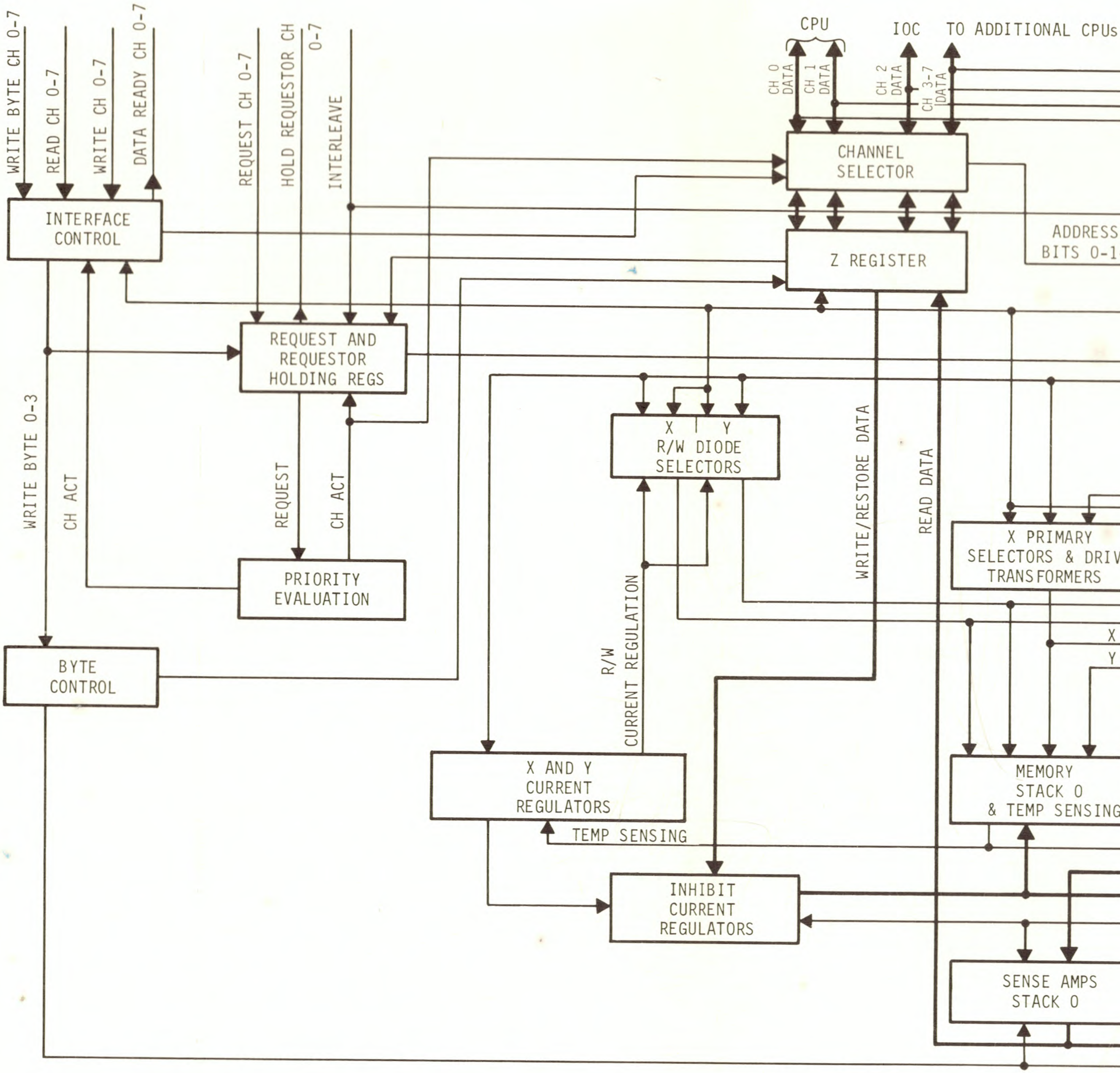

Figure 3-22.—Core memory unit block diagram.

# CHAPTER 4

# RADAR PRINCIPLES

*Radar* is an acronym for RAdio Detecting And Ranging. A radar system's primary purpose is the detection and location of an object (target) by means of a return signal (echo). Radar enables the detection of targets in the atmosphere or outer space at distances and under conditions beyond the capability of the unaided human eye. A radar can detect targets unimpaired by darkness, fog, clouds, smoke, or most other obstacles that would impair visual detection. Radars can determine a target's relative direction, range, velocity, and acceleration. The superiority of radar in determining these quantities at ranges far in excess of the capability of visual tracking has fostered the use of radar systems in air traffic control, collision avoidance, weather, mapping, early warning defense systems, and many other applications. FCs routinely maintain, operate, and use radar systems for detection, tracking, and missile guidance.

## RADAR BASICS

Radar operates on the basic principle of transmitting electromagnetic waves from a transmitter with sufficient power for a measureable amount of electromagnetic energy to be reflected back from the target and detected by the radar's receiver. Many methods of transmitting and receiving electromagnetic energy can be used. The method used most frequently is the *pulse method*. Radar, when mentioned in this chapter, refers to pulse radars unless otherwise stated. Other methods are discussed since radars maintained by FCs may use continuous wave (cw) as well as pulse methods, depending on the system.

### DECIBELS

A common term used in the discussion of radars is the *decibel* (dB), which is a shorthand way of expressing large ratios. If we increase radar transmitter power by a factor of 100 times, this is the same as a 20 dB increase. If we increase transmitter power 1,000 times, it would be the same as a 30 dB increase. It does not matter what power level we actually end up with, it is the ratio of the power level we ended up with compared to where we started. It is a 20 dB improvement in raising our power level from 1 watt to 100 watts or from 1,000 watts to 100,000 watts.

The reverse is also true. A 20 dB loss means the power is decreased to one-hundredth of its former value. With a 30 dB loss, we have only one-thousandth of the original power. It does not matter what the original power was. A 20 dB gain (or loss) means that the new power level is 100 times greater (or smaller).

Many electronic and mechanical devices operate in a logarithmic manner. Changes of power closely relate to changes in effects when expressed in decibels rather than ratios. The human ear is one such device. In fact, the decibel was originally used to denote the smallest change in audio power level that the human ear could detect.

The decibel value of a power ratio is equal to 10 times the common (base 10) logarithm of the ratio. For example, if a transmitter has an output of 50 watts and you make adjustments that increase the power level to 100 watts, the ratio of the two power levels is 100/50 = a ratio of 2:1 or 2. The common logarithm of the number 2 = 0.30 (from table of logarithms such as appendix 1 of *Mathematics*, Vol. 1, NAVEDTRA 10069). Substituting in the formula

**Table 4-1.—Decibels (dBm dBW) with Powers of 10 and Prefixes in Watts**

| dBm | dBW | WATTS WHOLE NUMBER OR DECIMAL NUMBER | MULTIPLE OR SUBMULTIPLE | PREFIX |
|---|---|---|---|---|
| +150 | +120 | 1,000,000,000,000 | $10^{12}$ | 1 TERAWATT |
| +140 | +110 | 100,000,000,000 | $10^{11}$ | 100 GIGAWATTS |
| +130 | +100 | 10,000,000,000 | $10^{10}$ | 10 GIGAWATTS |
| +120 | +90 | 1,000,000,000 | $10^{9}$ | 1 GIGAWATT |
| +110 | +80 | 100,000,000 | $10^{8}$ | 100 MEGAWATTS |
| +100 | +70 | 10,000,000 | $10^{7}$ | 10 MEGAWATTS |
| +90 | +60 | 1,000,000 | $10^{6}$ | 1 MEGAWATT |
| +80 | +50 | 100,000 | $10^{5}$ | 100 KILOWATTS |
| +70 | +40 | 10,000 | $10^{4}$ | 1 MYRIAWATT (10 kW) |
| +60 | +30 | 1,000 | $10^{3}$ | 1 KILOWATT |
| +50 | +20 | 100 | $10^{2}$ | 1 HECTOWATT (100 W) |
| +40 | +10 | 10 | $10^{1}$ | 1 DECAWATT (10 W) |
| +30 | 0 | 1 | $10^{0}$ | 1 WATT |
| +20 | −10 | 0.1 | $10^{-1}$ | 1 DECIWATT (100 mW) |
| +10 | −20 | 0.01 | $10^{-2}$ | 1 CENTIWATT (10 mW) |
| 0 | −30 | 0.001 | $10^{-3}$ | 1 MILLIWATT |
| −10 | −40 | 0.0001 | $10^{-4}$ | 100 MICROWATTS |
| −20 | −50 | 0.00001 | $10^{-5}$ | 10 MICROWATTS |
| −30 | −60 | 0.000001 | $10^{-6}$ | 1 MICROWATT |
| −40 | −70 | 0.0000001 | $10^{-7}$ | 100 NANOWATTS |
| −50 | −80 | 0.00000001 | $10^{-8}$ | 10 NANOWATTS |
| −60 | −90 | 0.000000001 | $10^{-9}$ | 1 NANOWATT |
| −70 | −100 | 0.0000000001 | $10^{-10}$ | 100 PICOWATTS |
| −80 | −110 | 0.00000000001 | $10^{-11}$ | 10 PICOWATTS |
| −90 | −120 | 0.000000000001 | $10^{-12}$ | 1 PICOWATT |

decibel = $10 \log_{base10} P$, where P is the power ratio, we have $10 \log_{base10} 2 = 10 (0.30) = 3$ dB.

Some of the more commonly used decibel power values are listed below:

| dB | POWER RATIO |
|---|---|
| 0.0 | 1.00 |
| 0.5 | 1.12 |
| 1.0 | 1.26 |
| 1.5 | 1.41 |
| 2.0 | 1.58 |
| 3.0 | 2.00 |
| 4.0 | 2.51 |
| 5.0 | 3.16 |
| 6.0 | 3.98 |
| 7.0 | 5.01 |
| 8.0 | 6.31 |
| 9.0 | 7.94 |
| 10.0 | 10.00 |
| 15.0 | 31.60 |
| 20.0 | 100.00 |
| 25.0 | 316.00 |
| 30.0 | 1,000.00 |
| 40.0 | 10,000.00 |
| 50.0 | $10^{5}$ |
| 60.0 | $10^{6}$ |
| 70.0 | $10^{7}$ |
| 80.0 | $10^{8}$ |
| 90.0 | $10^{9}$ |
| 100.0 | $10^{10}$ |

Decibels can be expressed in relationship to 1 milliwatt (dBm). Decibels can also be expressed in relation to 1 watt (dBW). Table 4-1 shows the powers of 10 and corresponding power levels in dBm and dBW, the decimal value and prefix. Additional information on logarithms can be found in the mathematics series NAVEDTRA 10069, 10071, and 10073.

## FREQUENCY UTILIZATION

The principles of radar are used throughout the electromagnetic spectrum from a few megahertz to the ultraviolet range (laser radar). Table 4-2 shows the current radar frequency allocations according to the International Telecommunications Union (ITU). Several systems of designation have been used through the years. The radar band designation system identifies a frequency band by an alphabetic designation, such as L, S, and C. We can see these codes used in technical manuals and on some of the equipments themselves. Table 4-2 lists the radar band designations and includes for reference only the electronic warfare (EW) frequency band designations. The electronic warfare system also uses an alphabetic designation, but it does not correspond to the radar designations. The EW bands are used to designate electromagnetic counter measure (ECM) devices, and are not to be used to identify radar frequency bands, except from the EW countermeasures standpoint. Most of the radars you will encounter as an FC operate between 200 megahertz and 40 gigahertz in the UHF, SHF, and EHF bands.

## FREQUENCY, WAVELENGTH, AND VELOCITY

Radio waves in space are characterized by *frequency* (f), or rate of oscillation, measured in hertz (Hz), formerly cycles per second (cps). The prefixes kilo, mega, and giga are used with hertz to denote $10^3$, $10^6$, and $10^9$ respectively, with the corresponding abbreviations kHz, MHz, and GHz. The wavelength ($\lambda$, Greek letter lambda) is the spatial separation of two successive wave crests in space. The waves travel in empty space (also called free space) at a velocity c = 186,300 miles per second, 161,875 nautical miles per second, 299,793 kilometers per second, 328 yards per microsecond, or 984 feet per microsecond. These quantities are related in free space by the expression:

$$\lambda = \frac{c}{f} .$$

In space that is not empty (air, dielectric materials), the velocity of propagation v is generally different from c, and the wavelength $\lambda = v/f$ then differs from the free space wavelength. The ratio $c/v = n$ is called the *index of refraction* of the propagation medium. For many radars it is permissible to assume $n = 1$, and, therefore, $v = c$. The velocity c is often referred to, without qualification, as the speed of radar wave propagation, though the symbol c specifically means the speed in empty space (vacuum). In the un-ionized part of the Earth's atmosphere, v is slightly less than c.

## WAVE POLARIZATION

Electromagnetic waves in space are characterized by three vector directions: (1) the direction of propagation; (2) the direction of the electric vector (E); and (3) the direction of the magnetic vector (H). At any given point in space and at a particular instant of time, these three vectors are always mutually perpendicular (fig. 4-1). The direction of the electric vector is the

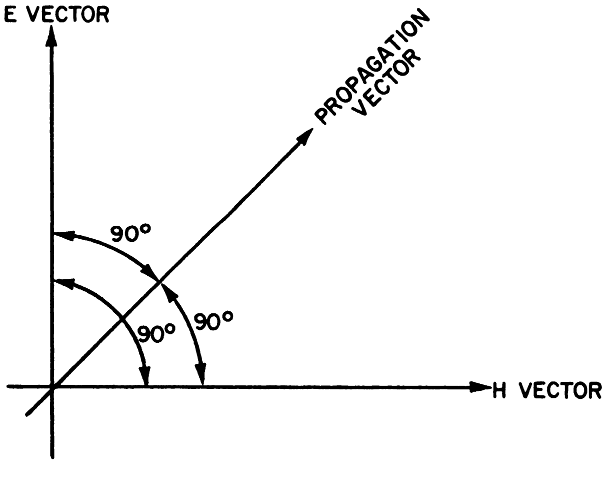

Figure 4-1.—Wave polarization.

Table 4-2.—Radar Frequency Allocations

| RADAR BAND DESIGNATIONS | | ITU FREQUENCY BANDS | | EW(ECM) FREQUENCY BANDS | | CURRENT ITU FREQUENCY ALLOWANCES FOR RADAR |
|---|---|---|---|---|---|---|
| | | HF | 3-30 MHZ | A | 0-250 MHZ | |
| | | VHF | 30-300 MHZ | | | 216-225 MHZ |
| P | 230-1000 MHZ | | | B | 250-500 MHZ | 420-450 MHZ |
| | | UHF | 300 MHZ-3 GHZ | C | 500-1000 MHZ | 890-940 MHZ |
| L | 1-2 GHZ | | | D | 1-2 GHZ | 1215-1400 MHZ |
| S | 2-4 GHZ | | | E | 2-3 GHZ | 2300-2550 MHZ |
| | | SHF | 3-30 GHZ | F | 3-4 GHZ | 2700-3700 MHZ |
| C | 4-8 GHZ | | | G | 4-6 GHZ | 5255-5925 MHZ |
| | | | | H | 6-8 GHZ | |
| X | 8-12.5 GHZ | | | I | 8-10 GHZ | 8500-10,700 MHZ |
| | | | | J | 10-20 GHZ | 10-10.68 GHZ |
| $K_u$ | 12.5-18 GHZ | | | | | 13.4-14.4 GHZ<br>15.7-17.7 GHZ |
| K | 18-26.5 GHZ | | | K | 20-40 GHZ | 23-24.25 GHZ |
| $K_a$ | 26.5-40 GHZ | | | | | 33.4-36 GHZ |
| MM | >40 GHZ | EHF | 30-300 GHZ | L | 40-60 GHZ | 59-64 GHZ |
| | | | | M | 60-100 GHZ | 76-81 GHZ<br>92-95 GHZ<br>95-100 GHZ |
| | | | | | | 126-134 GHZ<br>134-142 GHZ<br>144-149 GHZ<br>231-235 GHZ<br>238-241 GHZ<br>241-248 GHZ |

polarization of the wave. For waves that are *horizontally polarized*, the propagation vector is horizontal (or nearly so), and the electric vector is also horizontal. For waves that are *vertically polarized*, the propagation vector is horizontal (or nearly so), but the electric vector is vertical, with the magnetic vector now horizontal. If the electric vector at a given point in space rotates at the radio frequency, the polarization is called *elliptical* or *circular*, depending on whether the vector magnitude varies or remains constant as it rotates.

## BASIC RADAR PRINCIPLES

The radar detection of a target is based on the transmission and reception of electromagnetic waves that are reflected from the target at a finite time after the transmission from the radar. By measuring the time required for the reflected waves (echo) to return, the distance to the target can be computed. By focusing the transmitted waves into a narrow beam (much like a searchlight) and by using the same focusing technique on reception, the direction of the target can be determined. By observing the target's change of position with time, its velocity can be computed. The radial component of the target's velocity can also be determined by measuring the Doppler shift ($f_d$) of the received signal relative to the transmitted frequency.

### Radar Classifications

As FCs, we are concerned with two classifications of radars—surveillance and tracking radars. Search radars fall in the *surveillance classification* and fire control radars fall in the *tracking classification*. This is not to say that surveillance radars cannot perform tracking or tracking radars cannot perform search functions. The classification only identifies a radar by its primary function or purpose.

### Target Location

Shipboard surveillance radars are used to detect the presence of a target and to determine its position. The fire control tracking radars refine the target position data. A 2-D (two-dimensional) radar determines (1) target range (R) and (2) azimuth angle in degrees. A 3-D (three-dimensional) radar determines (1) range, (2) azimuth, and (3) elevation angle in degrees relative to the horizontal plane. Tracking radars determine the same target data as a 3-D radar but with greater accuracy.

The Navy unit of distance is the nautical mile; 1 *nautical mile* equals 1,852 meters, or about 6,076 feet. Radar indicators are calibrated in mile units of 6,000 feet or 2,000 yards (radar mile). This facilitates conversion to range in yards, which is the standard unit of range used in fire control systems and weapons systems. The target height can be calculated from the range and elevation angle. Accurate height calculation requires consideration of the Earth's curvature and also a correction for the slight downward bending of the radar beam path in the atmosphere because of an effect called *refraction*. In most systems, this calculation is performed by a computer.

The target range is determined by measuring the time that elapses between the transmission of a pulse and reception of a target echo. The relationship between the echo delay time (t) in microseconds, the target range (R) in radar miles, and the speed of propagation (c) is

$$R = \frac{ct}{2} \text{ or}$$

$$t = \frac{2R}{c} .$$

Using the approximation of 2,000 yards equal to 1 nautical mile (only a 1% error), the time required for rf waves to travel 1 nautical mile and then return (total travel of 4,000 yards) is 12.2 microseconds.

$$t = \frac{4{,}000 \text{ yds}}{328 \text{ yds}/\mu\text{sec}} = 12.2\ \mu\text{sec}$$

The time required for the radar signal to travel a round-trip distance of 2,000 yards is 6.1 microseconds (1,000 radar yards).

The accuracy of target range measurement is limited by the accuracy of the timing clock and the pulsewidth. Accuracy is about one-tenth the range extent of the pulse. This is about 160 yards per microsecond of pulsewidth. The accuracy of angle measurement is limited by the antenna beamwidth in the plane of the measurement and is on the order of one-tenth the beamwidth.

### Radar Resolution and Ambiguities

The radar resolution, or ability to distinguish between two targets that are close together in range and/or angle (fig. 4-2), is approximately defined by the range extent of the transmitter pulse (pulsewidth) and the angular width of the antenna beam (beamwidth) in the plane of measurement. When two or more targets exist within the same range-angle resolution cell, it is very difficult to distinguish between the targets, even though there may be some *beating* caused by the alternate in-phase and out-of-phase relationship of the different target echoes.

*Range ambiguity* can occur when a received echo from one transmit/receive cycle of the radar is processed during the interval of a second or succeeding transmit/receive cycle. The apparent target range is reported within the expected range limits of the radar; however, the actual range is much greater.

*Angle ambiguity* can occur if the antenna pattern has significant radiation and reception of minor lobes. If a minor lobe is of sufficient strength to result in a detectable echo from a target, this echo may be interpreted as a main-lobe echo, and the angle associated with it will be in error by the amount of angular separation of the main lobe and minor lobe.

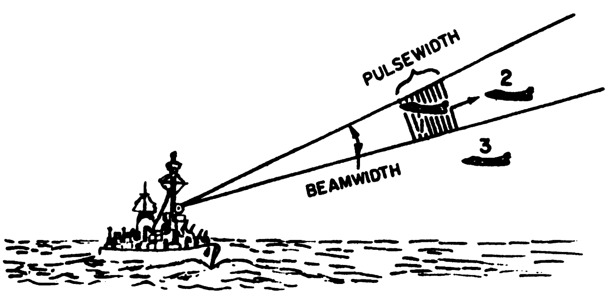

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Figure 4-2.—Radar resolution.

### Target Velocity

Ordinarily, target velocity is not directly measured by pulse radars, but the radial component can be measured directly by Doppler radars. Normally, target velocity is computed from position-versus-time data by either the radar computer or other data processing systems, such as the Navy Tactical Data System, (NTDS). If a target moves distance d in time t, its speed v is given by $v = d/t$. Continuous-wave radars can obtain a direct measurement of target radial velocity by measuring the frequency difference between the transmitted signal and the echo signal. If the frequency shift is upward, the target is moving toward the radar. If the frequency shift is downward, the target is moving away from the radar. Normally, the cw Doppler technique is not used for surveillance (search) radars because target position is easier to determine and more precise with pulse radars.

## WAVE PROPAGATION

Electromagnetic waves travel outward from a radiating point source at the same speed in all directions, in either free space or in any uniform propagation medium. Their energy and power are spread over the surface of an expanding sphere. This means that the power density for a given area decreases as the sphere expands. If the distance from the source increases by a factor of 2 (doubles), then the density of the power decreases by a factor of 4 (one-fourth). Stated another way, power density varies inversely with the square of the distance from the source. This is the well known *inverse square law*. Since this effect occurs on both the outward and return paths in free-space propagation, the received echo signal power from a radar target ($P_r$) varies inversely as the fourth power of the target range:

$$P_r = \frac{1}{R^4} .$$

Although free-space conditions never apply exactly in real radar operation, many situations occur where radar operation approximates free-space conditions so that this approximation can be used with negligible error.

### Atmospheric Absorption

Radar waves traveling in free space are not absorbed by the propagation medium, even though they are weakened by the spherical spreading as they progress. In the Earth's atmosphere and in other propagation media containing material particles, there is some absorption of the waves, which causes additional weakening or attenuation.

The absorption in the Earth's atmosphere is caused by the oxygen and water vapor molecules. The water vapor molecule and oxygen content vary considerably in the atmosphere. On a clear day, with a low relative humidity, there would be less loss through absorption than on a foggy or rainy day. The calculation of atmospheric losses is extensive and best left to the computer. Changes in frequency can also change the amount of loss with the same atmospheric conditions. A change in the elevation angle that the wave is transmitted from also changes the amount of absorption, with a higher angle yielding less absorption, because the atmosphere is thinner at higher altitudes.

### Refraction

For the purpose of velocity and distance calculations, the refractive index of the Earth's atmosphere can be assumed equal to 1. However, it is actually about 1.0003 at sea level and decreases to 1 exponentially with increased height. This small negative gradient produces a slight downward bending or curvature of electromagnetic waves in the atmosphere (fig. 4-3). The effect is large enough to be important in precise target location calculations at long radar ranges.

Under certain abnormal atmospheric conditions, a layer can exist in the atmosphere in which the refractive index is steeper than normal, resulting in sufficient bending of the rays to produce trapping. The *trapped rays* propagate within this layer, or duct, following the curvature of the Earth beyond the normal radar horizon. This effect, also called *ducting*, may occur frequently in certain climatic areas, but it is not reliable enough to be a basis for dependable beyond-the-horizon radar detection.

### Horizon Effect

When a target goes below the Earth's horizon, it cannot be detected because the solid material of the Earth blocks (shadows) the radar signal. Assuming standard atmospheric refraction and no ducting, the maximum horizon range due to the horizon limitation ($R_h$) in nautical miles when the

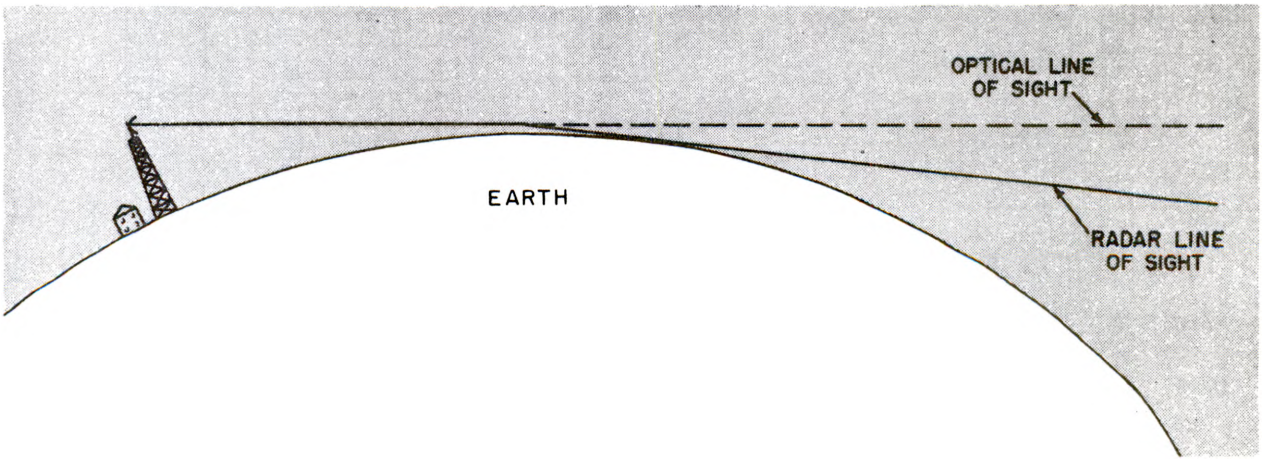

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**Figure 4-3.—Extension of radar horizon by atmospheric refraction.**

radar antenna height in feet is $h_a$, is given (approximately) by

$$R_h = 1.23\sqrt{h_a}\,.$$

This formula takes into account the slight downward bending of the waves caused by refraction (fig. 4-3). It is evident from the formula that the horizon distance ($R_h$) can be increased by increasing the antenna height.

## PROCESSING AND DETECTING ECHO SIGNALS

Radar receivers are capable of amplifying very weak echo signals (measured in microvolts or micro-microwatts) to almost any desired level. However, there is a particular signal strength, at the receiver input, below which radar detection cannot succeed regardless of the amount of amplification employed. The fundamental limitation in detecting weak signals is imposed by the presence of minute voltage fluctuations called *noise*. These fluctuations are always present, at some level, in all receivers. Through good receiver design and appropriate signal processing, the effects of noise can be minimized, but it can never be entirely eliminated. Noise is caused by the thermal agitation of electrons in conductors and resistors and by other unavoidable effects. Proper maintenance can maintain a radar receiver so that no additional noise is introduced and the receiver sensitivity is still high for low-signal levels. When signals become sufficiently weak in relation to the noise fluctuations, it is impossible to decide reliably whether a particular voltage increase in the receiver output is caused by a signal or merely a chance fluctuation of the noise.

The detectability of an echo signal is based on probability. That is, a *probability of detection* is associated with a specified signal level. Associated with the probability of detection is the unavoidable risk of falsely concluding that a signal is present, when, in fact, it is only noise. The probability of this occurring is called the *false alarm probability*. The ideal situation is where the probability of detection is very high with respect to the probability of false alarm.

For a receiving system, signal processing method, and target detection decision procedure, the probabilities of detection and false alarm are based on functions of the signal-to-noise power ratio (S/N) required for detection. The most effective practical means of processing to optimize the existing signal-to-noise power ratio is by integrating successive pulses. In this way, detection is based on the combined (additive) effect of several pulses instead of a single pulse.

The number of pulses integrated for a radar can vary considerably. For search radars where the radar beam is sweeping past a target, the number of echo pulses available for integration is considerably less than a tracking radar, where the beam is held on the target for a much longer period of time. Another problem encountered with search radar detection is the larger variation in echo amplitude, because the radar beam is not centered on the target. As the beam sweeps past a target, the echo goes from very weak to strong and then back to weak, varying from undetectable to easily detectable (fig. 4-4).

The measure of the minimum signal strength required for detection is called the ***minimum detectable signal-to-noise power ratio***. This is commonly shortened to MDS, the minimum detectable signal. MDS is expressed in decibels and referenced to 1 milliwatt (dBm). In radars maintained by FCs, you will find an MDS in the neighborhood of at least −90 dBm. This means that the radar is capable of detecting a signal 90 dB smaller than 1 milliwatt, or 1 picowatt ($10^{-12}$ watts).

### Transmitter Power

The ability to detect a given target is determined by the power level of the echo signal at the receiver. Since it is impossible to make the target bigger to reflect more power, we can only change the factors we can control—to increase the amount of power we send out. Radar systems use two basic types of energy transmissions: *pulse* and *continuous wave*. Increasing the transmitted power with either type of transmission increases the echo signal strength for a given target, and thus increases the S/N ratio and the probability of detection.

For pulse radars there are other characteristics that can be changed to increase the transmitted power. The average transmitted power is the same as the peak transmitted power for cw radars, but it is dependent on three factors for pulse radars (peak power, pulsewidth, and pulse repetition time). Pulse radar measures range in terms of the time interval between transmission and reception of the echo signal. The pulse repetition time (PRT) must be of sufficient duration to allow the echo pulse to return from the maximum range of the radar, otherwise it could be obscured by the next transmitter pulse or produce an ambiguous range. The total time required for the completion of a cycle, the pulsewidth (PW) plus the resting time, is called the *repetition time*. Figure 4-5 shows the relationship between pulsewidth, pulse repetition time, resting time, and peak and average power for a pulse radar. The necessary time for an echo to return determines the maximum frequency for pulse repetition. The minimum range that an echo can be detected is effected by the pulsewidth of the transmitted pulse. If a target is so close that the echo signal returns before the transmitter is cut off, the echo is obscured by the transmitted pulse and undetectable. The pulsewidth must be small to detect nearby targets and yet contain sufficient power to detect targets at maximum range. The useful power of the transmitter is contained in the radiated pulses and is called the *peak power*. A pulse radar is not transmitting for much of its total cycle, therefore, the average power is quite low in relation to the peak power. The relationship between peak and average power can be expressed by the following equation:

$$\text{Average power} = \text{peak power} \times \frac{\text{pulsewidth (PW)}}{\text{pulse repetition time (PRT).}}$$

By using the reciprocal of pulse repetition time (pulse repetition frequency = PRF), another version of the formula is derived:

$$\text{Average power} = \text{peak power} \times \text{PW} \times \text{PRF.}$$

Increasing peak power, pulsewidth, or PRF increases the average power. The relationship of average power to peak power can be expressed

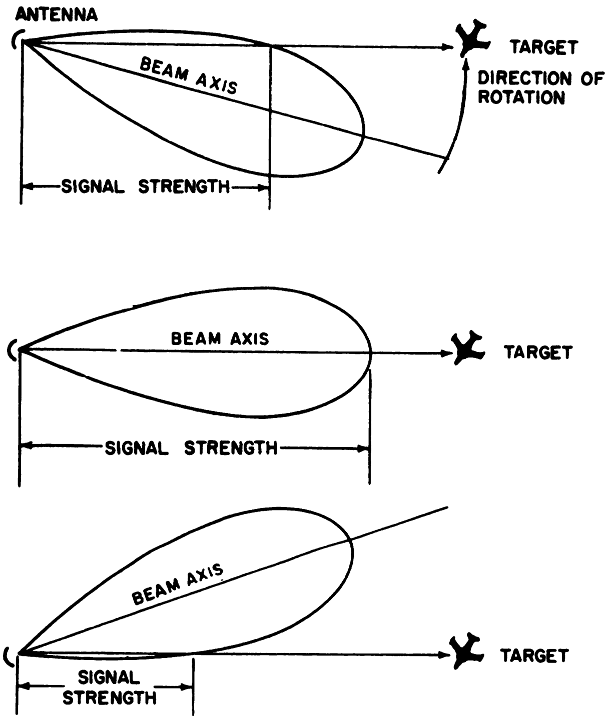

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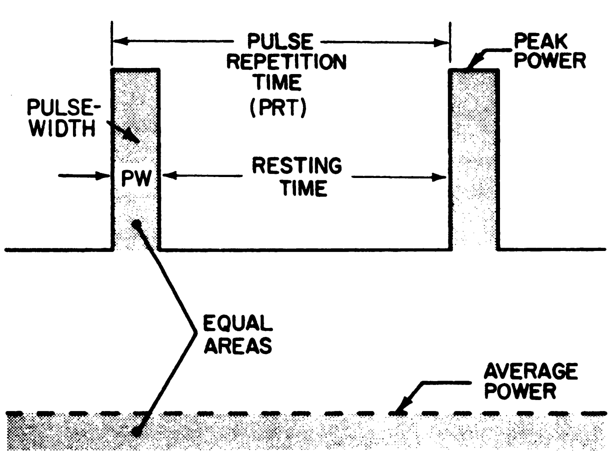
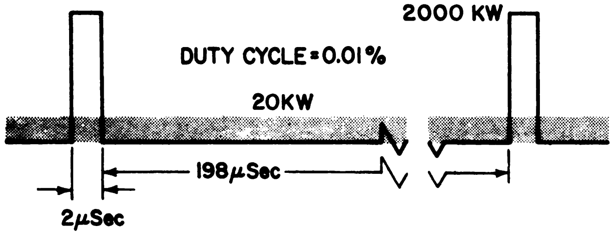
Figure 4-4.—Target echo strength variations.



167.759

Figure 4-5.—Pulse repetition time.



167.760

Figure 4-6.—Duty cycle.

in duty cycles (shown in fig. 4-6) and represented as follows:

$$\text{duty cycle} = \frac{\text{average power}}{\text{peak power}} = \frac{PW}{PRT} \text{ or } PW \times PRF.$$

For example, a 2-microsecond pulsewidth at a PRF of 5,000 Hz gives a duty cycle of 0.01. If the peak power were 200 kw for the same duty cycle, average power would equal peak power times duty cycle or 200 kw × 0.01 = 2,000 watts average power.

Consider the relationships between power, pulsewidth, and repetition rate. Recall that range resolution and accuracy are dependent on the pulsewidth and timing clock. There are methods of increasing the power by increasing the pulsewidth without sacrificing the range resolution or accuracy. One method in common use for fire control radars is *pulse compression*. In this method, pulsewidth is increased considerably from the normal 1 microsecond or less. The pulse is then encoded with an FM, pulse code, or phase code type of modulation. After the echo is received, the modulation is decoded and the pulse is compressed into a narrow pulse for further processing. Minimum range is sacrificed for more reliable long-range detection, because more power is contained in the transmitted pulse.

Techniques like pulse compression are used because, with current technology, peak power levels on the order of about 10 megawatts is the output limit of high-power transmitter tubes and transmission lines such as waveguides.

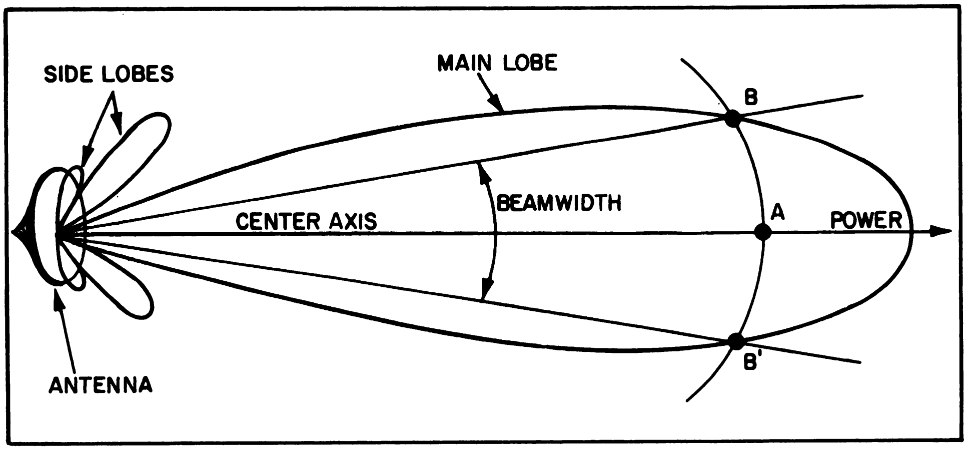
### Antenna Factors

The antenna design affects the detection of a target considerably. A look at different ships will show a wide variety of antenna designs. Each design is suited to the application to provide a suitable beamwidth and gain factor.

**ANTENNA GAIN.**—The maximum power gain of an antenna is a function of its directivity and radiation efficiency. The directivity is the electric-field-intensity pattern in spherical coordinates. The radiation efficiency is the ratio of the power delivered to the antenna to the total power actually radiated. The antenna gain is usually expressed as a power gain in dB. Antenna gain for a receiving function is the ratio of the total incident (echo signal) power and the total signal power extracted from the incident power. The reciprocal of the antenna radiation efficiency is the *antenna loss factor*.

**ANTENNA BEAMWIDTH.**—This factor affects detection by the strength of the echoes available for integration when the antenna is receiving. Beamwidth affects the antenna directivity, thereby effecting the amount of power available at the target. A narrow beamwidth increases detection probability with a tracking radar but decreases it for a search radar, since fewer pulses are available for integration when the antenna is scanning.

Antenna beamwidth can be measured by power readings taken at a distance from the antenna. With a directional antenna, where the electromagnetic energy is focused into a beam, the strength of the radiated field varies as the distance from the center of the beam changes. In figure 4-7, point A represents the center of the beam (maximum power). Power measured away from the beam center, while maintaining the same radius from the antenna, decreases as the distance increases. At some distance, the power level increases again but does not reach the strength that was measured in the center of the beam. The points where power increases away from beam center are the locations of the *side lobes*. Moving away from beam center (point A) to point B or $B^1$ produces a power level decrease of 3 dB, or half power. The angle bisected between the half-power points (B and $B^1$) measured about the origin (antenna) is called the *beamwidth*. The beamwidth of the side lobes can also be measured using the same technique. Beamwidth is expressed in degrees, and narrow beams of less than 1 degree



55.396

Figure 4-7.—Antenna radiation pattern.

are found in some fire control radars. Ideally, we would want a beam that did not spread out spherically away from the antenna. This is most closely achieved with only coherent light such as the laser. Figure 4-7 only shows one axis (two dimensions) of measurement. Most tracking radars use a symmetrical beam where the beamwidth is identical in both the horizontal and vertical axis and forms a circular pattern. Some radars, such as 2-D search radars, use a beam that is elliptical and narrow in the horizontal axis and wide in the vertical axis so that a larger vertical volume is covered.

### Target Cross Section

The cross-sectional reflective area of a target also affects the detection probability. The cross section of a given target changes as the target aspect changes. A jet fighter closing straight on the radar would present less of a reflective area than when it is crossing. A cruise missile closing would present a much smaller reflective area than a multiengine bomber that is closing.

We do not have control over many of the factors affecting target detection. Those factors we can control are controlled by being meticulous in maintaining the peak condition of the radar transmitter, receiver, antenna, transmission lines, and signal processing equipment.

## RADAR SYSTEMS

The two basic types of energy transmission employed by radar systems are pulse and continuous wave (cw). The basic principles of radar have been discussed previously. Now, let us look at radar systems more closely.

### PULSE RADARS

Figure 4-8 shows a simple pulse radar. The radar signal is generated by the transmitter and radiated into space by the antenna. The duplexer enables the use of a single antenna to transmit and receive the radar signal. The return echo signal is mixed with a local oscillator (LO) signal to produce an intermediate frequency (IF) signal at a lower frequency than the transmitter. Intermediate frequencies of about 30-60 MHz are commonly used because signal handling is easier to accomplish at the lower frequencies than at the transmitter frequencies. The IF/filter conditions the echo signal through amplification and filtering of extraneous signals. The IF signal is then sent to the second detector where the IF is converted to a lower frequency video signal. The

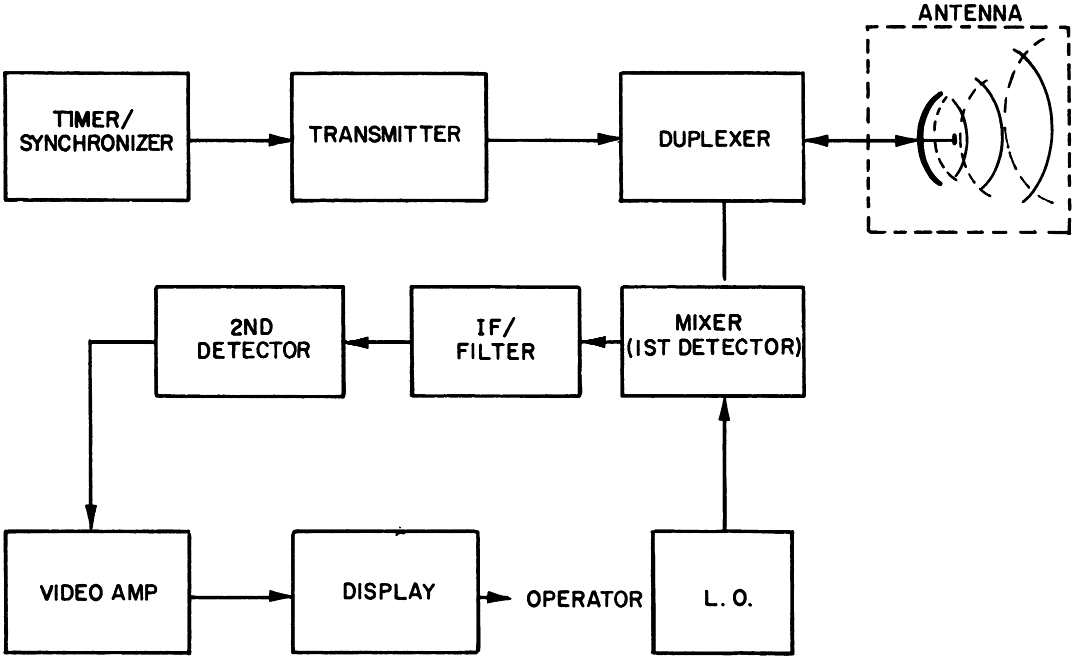


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Figure 4-8.—Basic pulse radar.

video signal is then processed for display by a video amplifier. The display is usually a cathode-ray tube (CRT) device that is monitored by an operator. The timer/synchronizer controls the repetition frequency of the transmitter. The timer can also provide a zero range start signal for the display device.

Actual pulse radar systems are more complex than depicted in figure 4-8, but they contain the same basic functional areas. A search radar requires additional circuitry to indicate antenna azimuth position coincident with a particular target echo. Additional circuitry might be added to a search radar for moving target indication (MTI) and to filter out stationary targets, land mass, and clutter from weather and the sea state. A tracking radar, such as a fire control radar, would require additional circuitry to accurately measure target range, azimuth, and elevation. Circuitry is also required to keep the antenna pointed at the target. So fire control radars have ranging and angle tracking systems included.

## SCANNING

For a radar to track a target, some means of keeping the radar beam pointed at the target is required. To do this, the radar system must be able to determine which direction the radar beam must be moved so that the target remains in the center of the beam. A visual indication on a CRT can depict range and angle of the target in respect to the beam center. The operator can then move the beam by positioning the antenna to center the target. This technique has been used, but it is not very efficient or reliable. Today's systems use computer-aided automatic tracking systems and two basic scanning methods. The two basic scanning methods are mechanical and electronic scanning.

### Mechanical Scanning

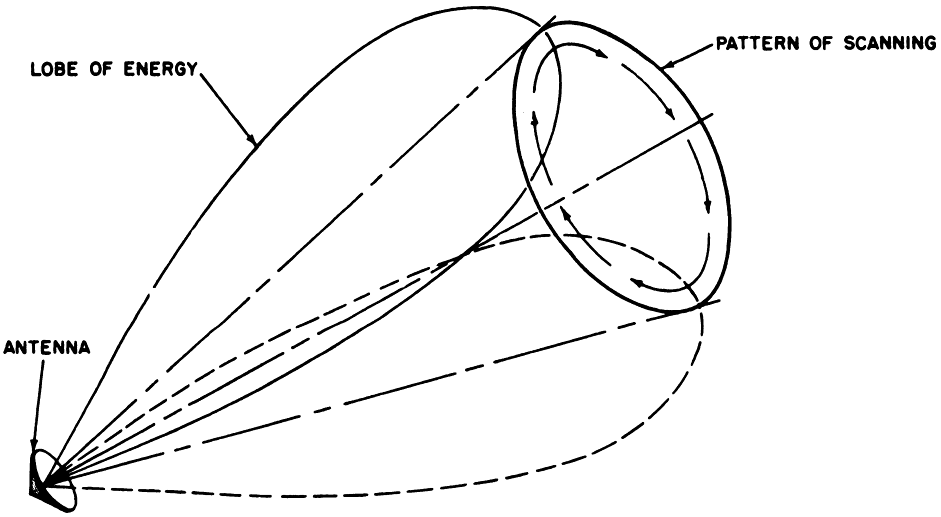
In mechanical scanning, the antenna can be moved in the desired pattern or the feed horn can be moved relative to a fixed reflector, or the reflector can be moved relative to a fixed feed horn. The most common mechanical scan technique used by fire control radars is a moveable feed horn relative to a fixed reflector. The most common mechanical scanning technique is called *conical scanning*.

**NUTATION.**—The nutation process is difficult to describe in words, but easy to demonstrate. Hold a pencil with both hands, one at the eraser end and the other at the point. While holding the eraser end as still as possible, move the point in a circle to form a cone. The motion of the pencil is nutation. The pencil point corresponds to the transmitting end of a waveguide feed. The important point is that the polarization of the rf beam does not change during a nutation cycle. This means that the axis of the moving feed horn must not change horizontal or vertical orientation while the feed is moving. The movement might be compared to that of a ferris wheel; the orientation of the seats remains vertical regardless of where they are on the wheel.

**NUTATING WAVEGUIDE.**—The waveguide feed is a metal pipe, usually rectangular in cross section. The open end of the waveguide feed faces the antenna disk reflector, and the energy it emits is bounced from the reflector surface.

A conical scan can be generated by nutation of the waveguide feed. In this process, the axis of the waveguide feed is nutated through a narrow conical pattern. This movement is fast (on the order of 30-60 hertz) and small in amplitude. To an observer, the waveguide feed would appear to be vibrating slightly. Figure 4-9 shows the conical pattern produced by nutating the rf beam. The amplitude of the nutation will determine the angle of the cone. The amplitude is kept small so that sufficient power is present in the center of the conical pattern for target tracking.

**ANGLE TRACKING.**—The radar's angle error-detecting circuits provide correction signals to the antenna/director drive circuits. The correction signals are proportional to the target displacement from the nutation axis of the antenna. Target displacement is detected by first locking on to the target in range, so that only that target is gated and used for angle tracking. Let us look at a series of echo pulses during one scan cycle with a target off of the center



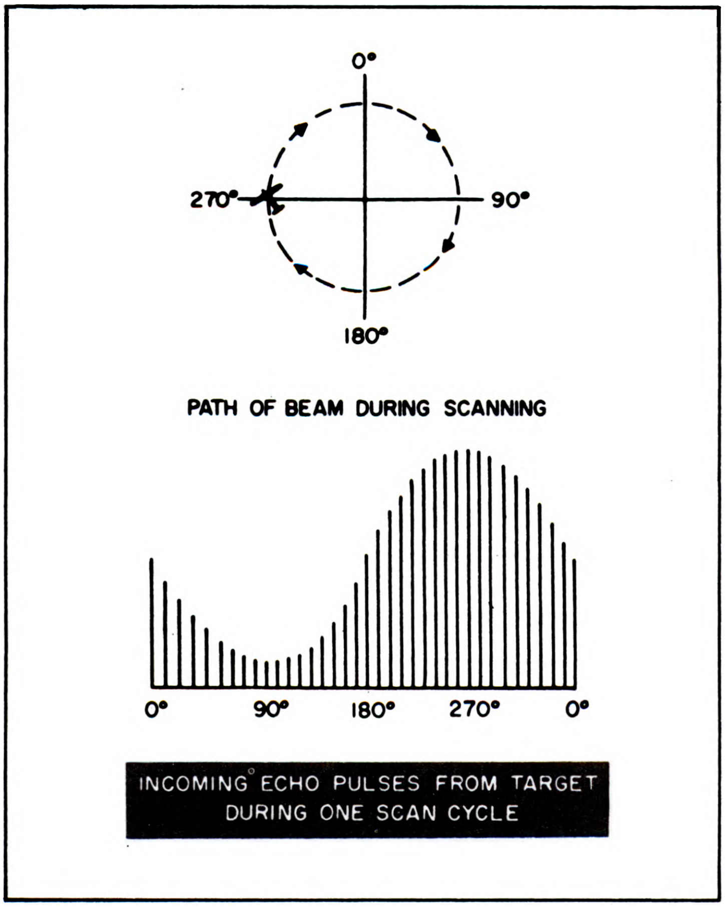
167.765

Figure 4-9.—A nutating lobe.

axis (fig. 4-10). With the radar range tracking the target, the target is in the left-hand portion of the antenna scan pattern. This should produce an angle error signal that will drive the antenna to the left, bringing the target into the center. Normally, with automatic tracking, the target will not be displaced very far from the beam center, but we exaggerate the error signal for illustration purposes.

When the center of the beam (fig. 4-10) is at 0°, the video return from the target is relatively small. As the center of the beam rotates in a clockwise direction, each successive video signal becomes smaller until it reaches 90°, where a minimum video signal is received. As the beam center continues to move, the amplitude of the video signals increases until a maximum signal is received when the beam center is on target at 270°. Further clockwise rotation moves the beam center away from the target, and the video reduces in amplitude.

Notice in figure 4-10 that the video signal for a complete nutation of the feed horn forms a sine wave. The sine wave is called the video envelope. The frequency of the video envelope is the same as the scan rate of the radar. The phase of the envelope is established by the position of the target relative to the center of the beam coverage of the radar. If the target had been to the right of the center of the coverage of the radar beam, the phase of the envelope in the figure would have been inverted. The amplitude modulation of the video envelope established the amount of target displacement from the center of the beam coverage of the radar. If the target had been in


0°
270°
90°
180°
PATH OF BEAM DURING SCANNING
0°
90°
180°
270°
0°
INCOMING ECHO PULSES FROM TARGET
DURING ONE SCAN CYCLE

12.321

Figure 4-10.—Amplitude and phase modulation of the video signal.

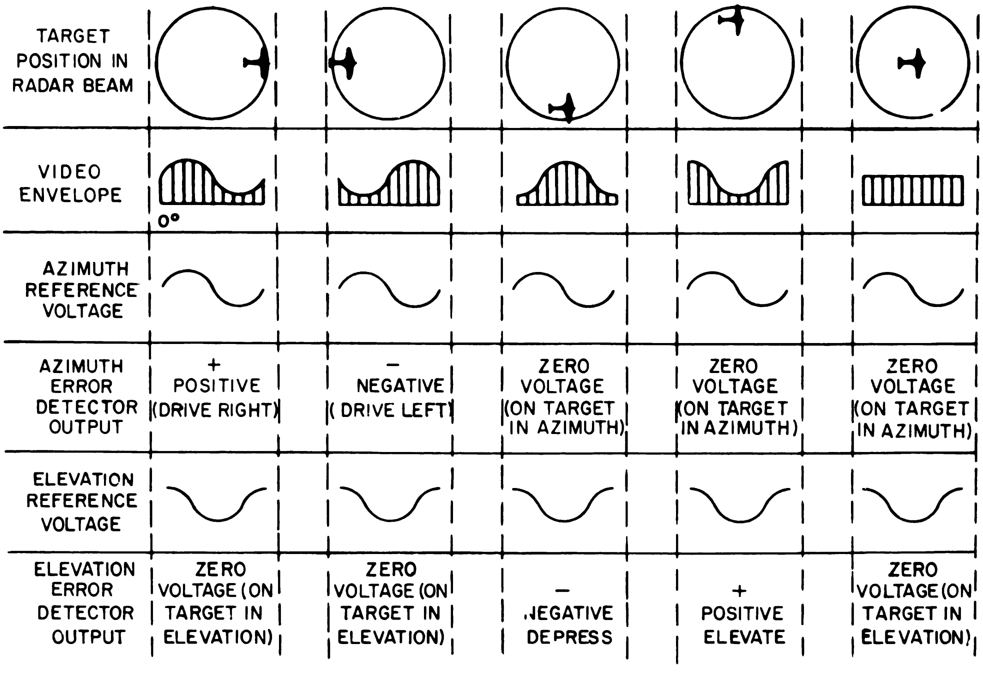
the center of the beam coverage, the video envelope would have been of a constant amplitude.

A two-phase reference generator in the antenna establishes the position of the feed horn relative to the nutation axis of the antenna. The generator provides the reference voltages for the angle error-detection circuits. The elevation reference voltage is 90° out of phase with the azimuth reference voltage. Each error detector circuit compares the phase of its reference voltage with the phase of its video envelope. The phase comparison (fig. 4-11) indicates the direction of the error. The amplitude modulation of the video envelope is compared to the amplitude of the reference voltage to determine the amount of error.

## Electronic Scanning

There are several techniques used for electronic scanning. The two most common techniques used in fire control radars are phasing and simultaneous lobing. Phasing causes an actual movement of the radar beam with respect to the antenna axis. Simultaneous lobing does not move the transmitted beam, instead the echo signal is scanned or compared.

**MONOPULSE.**—With monopulse or simultaneous lobing, all range, bearing, and elevation angle information of a target is obtained from, as the name implies, a single pulse. A tracking radar of this type normally produces a narrow circular beam of pulsed rf energy at a high pulse repetition rate. Each pulse is divided into four signals that are equal in amplitude and phase. The four signals are radiated at the same time from each of four feed horns that are grouped in a cluster. The radiated energy is focused into a beam by a microwave lens. Energy reflected from targets is refocused by the lens into the feed horns. The amount of the total energy received by each horn varies, depending on the position


TARGET POSITION IN RADAR BEAM
VIDEO ENVELOPE
0°
AZIMUTH REFERENCE VOLTAGE
AZIMUTH ERROR DETECTOR OUTPUT
+ POSITIVE (DRIVE RIGHT)
− NEGATIVE ( DRIVE LEFT)
ZERO VOLTAGE (ON TARGET IN AZIMUTH)
ZERO VOLTAGE (ON TARGET IN AZIMUTH)
ZERO VOLTAGE (ON TARGET IN AZIMUTH)
ELEVATION REFERENCE VOLTAGE
ELEVATION ERROR DETECTOR OUTPUT
ZERO VOLTAGE (ON TARGET IN ELEVATION)
ZERO VOLTAGE (ON TARGET IN ELEVATION)
− NEGATIVE DEPRESS
+ POSITIVE ELEVATE
ZERO VOLTAGE (ON TARGET IN ELEVATION)

12.332

Figure 4-11.—Phase comparison.

of the target relative to the beam axis. This is shown in figure 4-12. The four targets are at different positions with respect to the beam axis. Be sure to notice, and remember, that a phase inversion takes place at the microwave lens similar to the image inversion in an optical system.

The amplitude of returned signals received by each horn is continuously compared with those received in the other horns, and error signals are generated that indicate the relative position of the target with respect to the axis of the beam. Angle servo circuits receive these error signals and correct the position of the radar antenna/director to keep the beam axis on target.

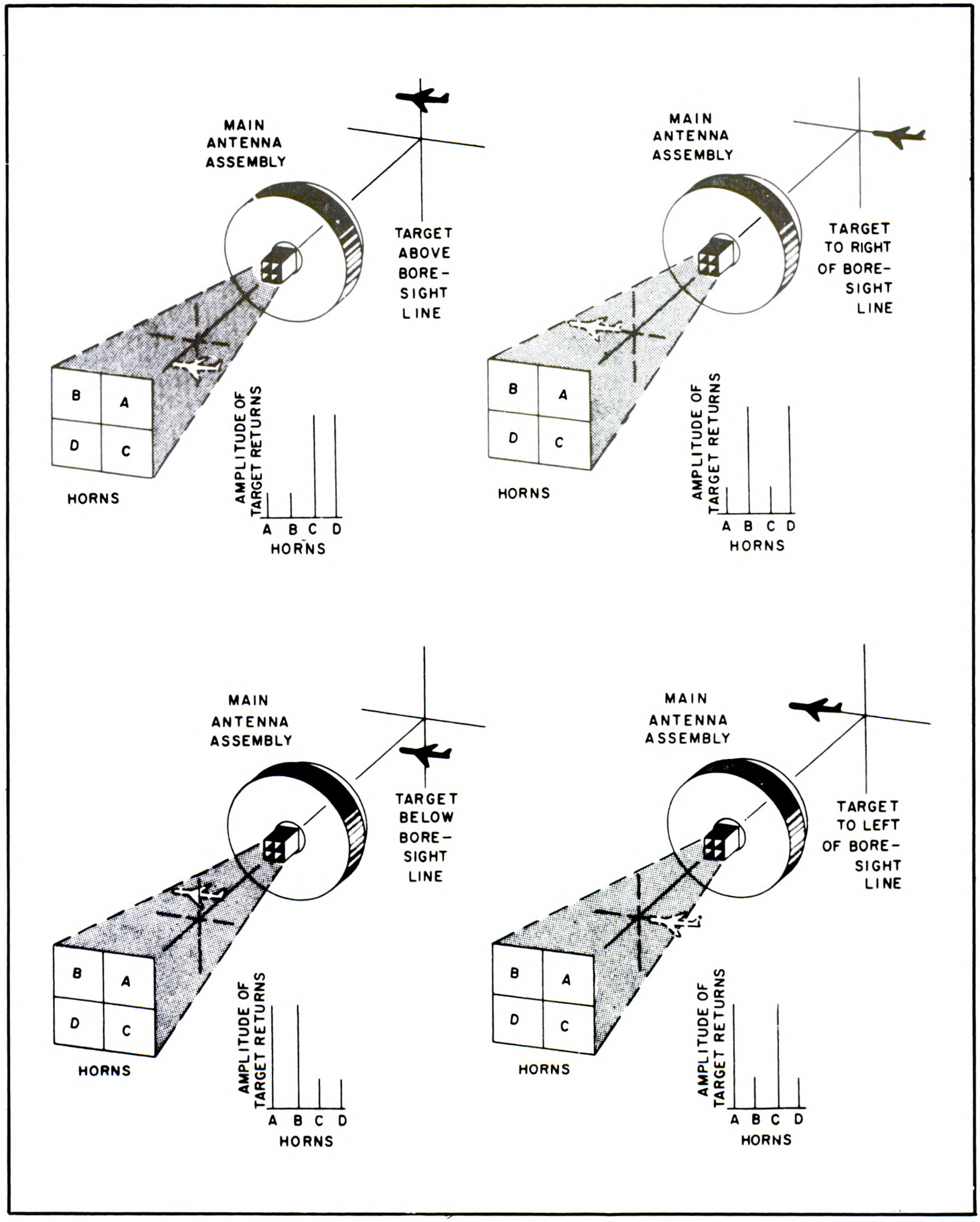
The traverse (train) signal is made up of signals from the sum of horns A and C and from the sum of horns B and D. By waveguide design, the sum of B and D is made 180° out of phase with the sum of A and C. These two are combined and the traverse signal is the difference of (A + C) − (B + D). Since the horns are positioned as shown in figure 4-12, the relative amplitudes of the horn signals give an indication of the magnitude of the traverse error. The elevation signal consists of the signals from horns C and D added 180° out of phase with A and B; that is, (A + B) − (C + D). The sum or range signal is composed of signals from all four feed horns added together in phase. It provides a reference from which target direction from the center of the beam axis is measured. The range signal is also used as a phase reference for the traverse and elevation error signals.

The traverse and elevation error signals are compared in the radar receiver with the range or reference signal. The output of the receiver may be positive or negative pulses, and the amplitude is proportional to the angle between the beam axis and the target. The polarity of the output pulses indicates whether the target is above or below, or to the right or to the left of the beam axis. If the target is directly on the line of sight, the output of the angle receiver is zero, and no angle tracking error is produced.

An important advantage of a monopulse tracking radar over one using conical scan is that the instantaneous angular measurements are not subject to errors caused by target scintillation. Scintillation is the rapid fluctuation of the echo signal amplitude as the target maneuvers or moves. The radar beams bounce off different areas of the target and cause random reflectivity, which may lead to tracking errors. A monopulse tracking radar is not subject to this error because each pulse provides an angular measurement without regard to the rest of the pulse train; scintillation does not affect the measurement. An additional advantage of monopulse tracking is that no mechanical action is required, such as a scanner.

**COSRO.**—Scanning the received signal by electronically switching between the antenna elements (feed horns) to produce a conical antenna receive pattern is called *conical scan* on *receive only* (COSRO). This technique of electronic scanning is used with monopulse transmissions and with single beam transmissions. Angle errors are produced in much the same way as mechanical conical scanning. COSRO is less effective than monopulse since many pulses are required to produce the target echo envelope. COSRO is used more effectively with cw radars using a separate receive antenna. COSRO may also be used as an alternate tracking method, such as an electronic counter-countermeasure (ECCM) technique. ECCM is discussed later in this chapter.

**PHASING.**—Phased array antennas use an electronic method of scanning. The techniques employed in phased array systems are discussed in more detail in chapter 5. Basically, the phasing method of scanning controls the phase of the rf signals fed to multiple feed horns, dipoles, or radiators. The angular position of the beam is determined by the relative phase of the signals at each element. When the phase of the signals applied is changed, the beam can be steered without moving the


MAIN ANTENNA ASSEMBLY
TARGET ABOVE BORE-SIGHT LINE
B
A
D
C
HORNS
AMPLITUDE OF TARGET RETURNS
A B C D
HORNS
MAIN ANTENNA ASSEMBLY
TARGET TO RIGHT OF BORE-SIGHT LINE
B
A
D
C
HORNS
AMPLITUDE OF TARGET RETURNS
A B C D
HORNS
MAIN ANTENNA ASSEMBLY
TARGET BELOW BORE-SIGHT LINE
B
A
D
C
HORNS
AMPLITUDE OF TARGET RETURNS
A B C D
HORNS
MAIN ANTENNA ASSEMBLY
TARGET TO LEFT OF BORE-SIGHT LINE
B
A
D
C
HORNS
AMPLITUDE OF TARGET RETURNS
A B C D
HORNS

257.29

Figure 4-12.—Monopulse variations of received energy with target position.

antenna. In figure 4-13, view A, the phase of the rf energy is the same for each element at the same time. This results in the plane of the wavefront parallel to the plane of the antenna, and a beam direction perpendicular to the antenna array. In figure 4-13, view B, changing the phase so that each element has a different phase applied causes the plane of the wavefront and thus the beam direction to be shifted. To increase the shift in the beam axis, an increase in the amount of phase shift between the elements is required. Another means of phasing uses changes in the transmitter frequency. Changing the frequency changes the wavelength; thus, with a fixed length of waveguide between elements, the phase relationship changes as the frequency changes. More on this method in the next chapter.

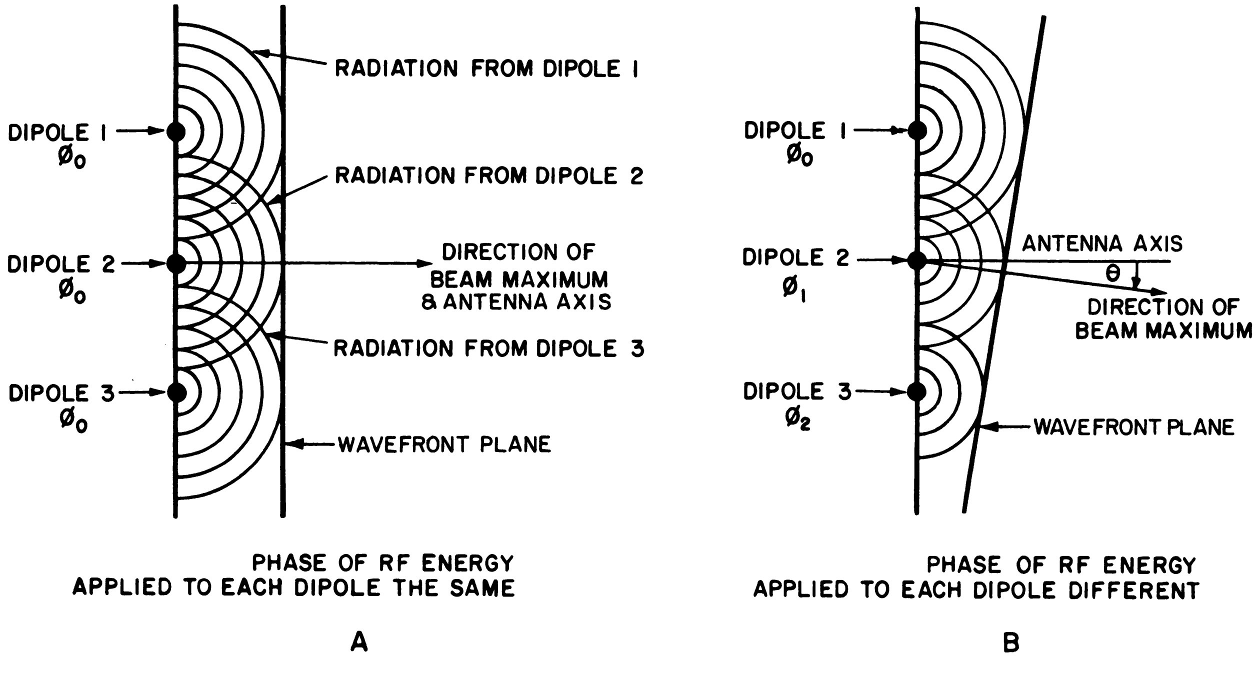
Phased arrays can be used for tracking by a monopulse receiving technique. The array is divided into quadrants, with each quadrant equivalent to one of the four horns. The sum of all four quadrants is compared to the sums and differences of different quadrants just as in monopulse. This technique is also adaptable to receive only antenna systems.

## CW RADAR

The cw radar employs a continuous transmission resulting in a continuous echo signal from a target. With a continuous echo signal, determination of the target range is impossible since there is no distinguishing start and stop of the echo signal. Leakage from the transmitter into the receiver has the same form and could be classified as a target. If the target is moving radially with respect to the transmitter, then a shift in frequency occurs. This shift is called the *Doppler shift* or *Doppler frequency*. A Doppler shift ($f_d$) allows distinguishing between the target and transmitter leakage.

### Doppler

The amount of Doppler shift is determined by the radial velocity of the target. The radial velocity is the apparent speed that the target is closing on



167.854

Figure 4-13.—Beam steering.

or going away from the radar (fig. 4-14). The radial velocity ($v_r$) can be determined by the formula $v_r = v \cos$ where v is the actual target speed. To determine the Doppler shift ($f_d$) for a radial velocity ($V_r$), use the formula

$$f_d = \frac{2v_r}{\lambda}$$

where $\lambda$ is the wavelength of the transmitted frequency. The wavelength should be in units that yield the desired result; yards would yield yards per second and meters would yield meters per second. A target can move in any direction and in a wide range in speed; therefore, the radial velocity can change considerably. If the target is moving at a 90-degree angle to the radar, then no Doppler shift is produced. If the target moves straight at or away from the radar, radial velocity will equal the actual target speed. We should note that the amount of Doppler shift is also dependent on the wavelength resulting from the transmitter frequency. A target radial velocity that produces a specific Doppler shift at 5,000 megahertz would produce twice as much at 10,000 megahertz.

### Cw Radar

Most cw radars use a separate antenna to receive since there is no transmit rest period as in pulse radars. This also improves the isolation between the transmitted signal and the received echo signals. Simple cw radars with a single antenna use a device called a ferrite circulator to act as a duplexer. These circulators are limited to lower power cw radars, because the amount of leakage from the transmitter to the receiver is about 20 to 30 dB down from the transmitter power level. For a 1-watt transmitter, this would be 1 milliwatt of leakage. More leakage than this could easily damage the receiver.

The basic cw radar, shown in figure 4-15, has the same basic components found in pulse radars. The main difference is the use of a separate antenna to receive and the use of filters to detect a Doppler shift. The filters are normally designed for the IF range, since working at the transmitter frequencies is more critical in the construction of circuits. The filters are set up to detect a particular narrow frequency band. The bands are set so they are adjacent to each other and cover the expected Doppler frequencies above and below the zero shift. The narrower the filter bandwidth, the more filters required, and the more discrete

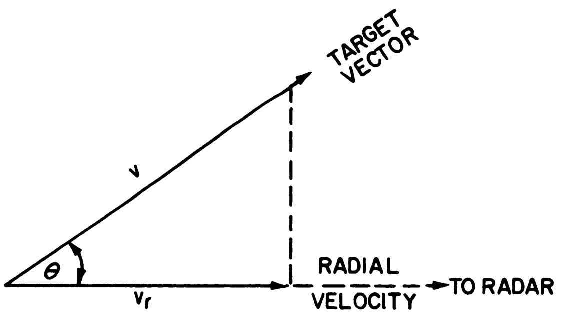


Figure 4-14.—Radial velocity.

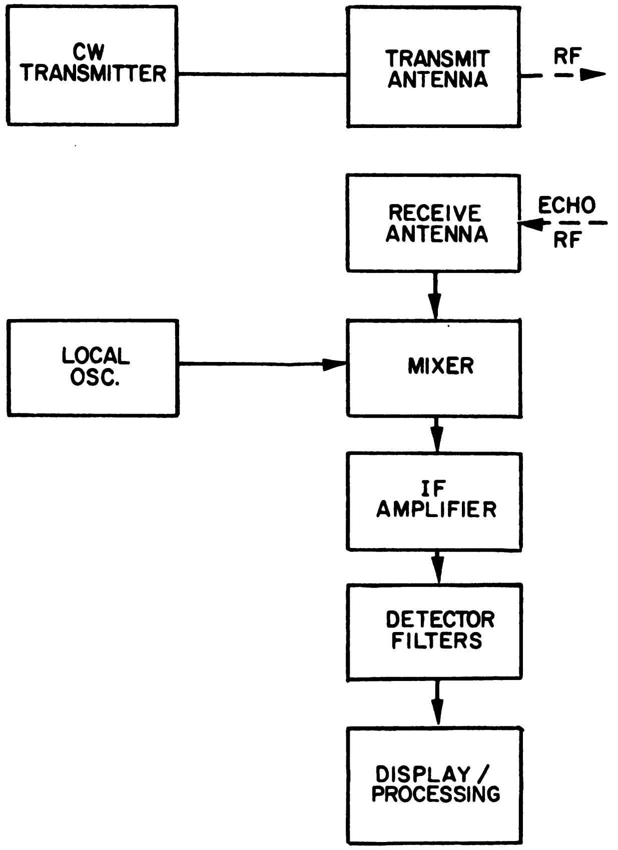


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Figure 4-15.—A basic cw radar.

velocities that can be determined within the receiver bandwidth.

With the basic cw radar, we cannot determine range of the target. We can track a target in angle. Angle resolution is determined the same way for both cw and pulse radars.

### FM-Cw Radars

The limitation of not being able to determine target range with cw radars can be overcome by frequency modulating the transmitted signal. The transmitter still transmits continuously, but the frequency is changed in a predetermined fashion. The modulation can be in the form of a sawtooth, triangular, sinusoidal, or of any shape as long as it produces a frequency change of known rate.

One form of modulation used is triangular FM'ing, shown in figure 4-16. Here we have a comparison of the transmitted signal with the echo signal received for a stationary target. Target range is determined by detecting the FM waveform of the echo signal and measuring the time (T) difference between the echo and transmit envelopes. The time difference is directly proportional to the target range. The frequency difference (Δf) also gives the target range, except at the turnaround points. This works for a stationary target, but most targets we are concerned with are moving.

A target moving radially produces a Doppler shift that is algebraically added to the echo signal. The Doppler shift raises (incoming target) or lowers (outgoing target) the echo signal waveform. This produces two separate frequency differences ($f_1$ and $f_2$), shown in figure 4-17. The difference between $f_1$ and $f_2$ is equal to the Doppler frequency ($f_d$). Subtracting $f_d$ from $f_2$ gives the Δf from which the range can be determined. Another calculation to find the target range is to add the $f_1$ and $f_2$ signals and then divide by 2. The Doppler shift frequency can be determined by dividing the difference between $f_1$ and $f_2$ by 2. No matter which form of modulation is used, range and velocity can be determined from an FM-cw radar.

Continuous-wave radars have an advantage over pulse radars when detecting moving targets in clutter. This is very useful when the clutter is caused by chaff, since detection is based upon the Doppler frequency and not a return pulse.

## PULSE-DOPPLER RADAR

With a simple cw radar, it is almost impossible to detect a stationary target because of clutter and leakage at the transmitter frequency. Moving targets are easily detected, but range determination is more difficult. A pulse radar can detect both stationary and moving

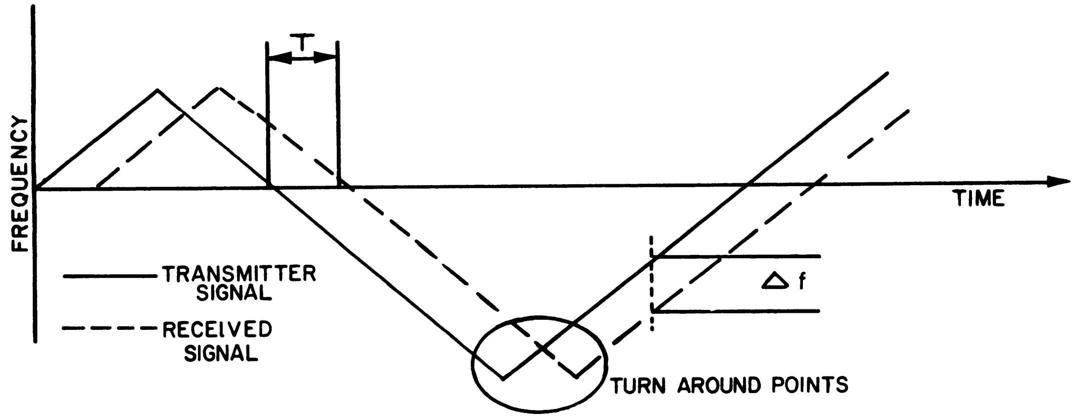

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Figure 4-16.—Triangular FM-CW (stationary target).

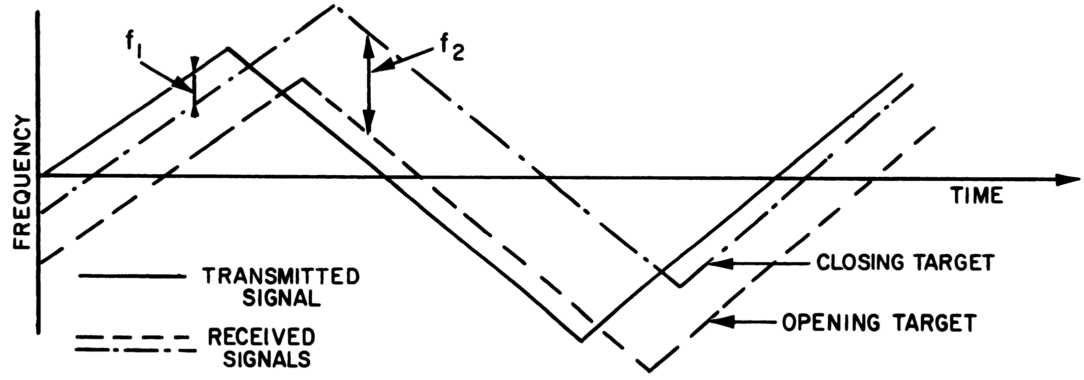

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Figure 4-17.—Triangular FM-CW (moving targets).

targets and determine range. A pulse radar echo signal also contains velocity information in the Doppler frequency information, but it is not normally used by a pulse radar.

By using the Doppler signal available on an echo signal, a pulse radar can detect a weak signal from a moving target in the presence of strong signals from large targets, such as a landmass and heavy seas. Pulse-Doppler radars use this Doppler shift signal. Pulse-Doppler radars can detect an aircraft flying close to a hill or mountain where the strong landmass echo would block detection with a pulse radar. Circuitry in the pulse-Doppler radar normally would reject the stationary target, allowing easy detection of the weak signal from the moving target. The pulse-Doppler radar has an advantage over a cw radar by being able to distinguish between two targets with the same radial velocity, but at different ranges. Pulse-Doppler radar, however, has some disadvantages too; blind target ranges, blind velocities, range and velocity ambiguities, and a reduction in maximum range capabilities. These disadvantages can be compensated for by using additional circuitry.

### Pulse-Doppler Theory

The ranging system of a pulse-Doppler radar is more complex than a pulse or FM-cw radar. A pulse-Doppler radar senses both range and velocity by time-sharing its waveform between these functions. To detect a Doppler frequency from the target echo, most pulse-Doppler radars use a much higher pulse repetition frequency (PRF) than pulse radars. The higher PRF decreases the time (PRT) between pulses, resulting in the possibility of a target echo returning at the time of the next transmission. This results in a blind spot in range. If the echo from the first pulse returns after the second pulse is transmitted, then a range ambiguity occurs. The range blind spot and ambiguities can be compensated for by changing the PRF over a wide range. For example, the fire control computer could adjust the radar PRF based on the expected range of a designated target. If the designation were for a target at 50 nmi (100 kyds), the PRF would be changed so that the second pulse would not occur until enough time had elapsed for the target echo to return for that range, plus an additional range interval for the acquisition and tracking gates. Varying the PRF over a wide range by computer control can resolve range ambiguities and blind ranges.

**DOPPLER SHIFT DETECTION.**—Pulse-Doppler radars can detect moving targets by the Doppler shift. *Moving target indication* (MTI) is a process used mostly to detect moving targets with pulse-Doppler search radars, and it is

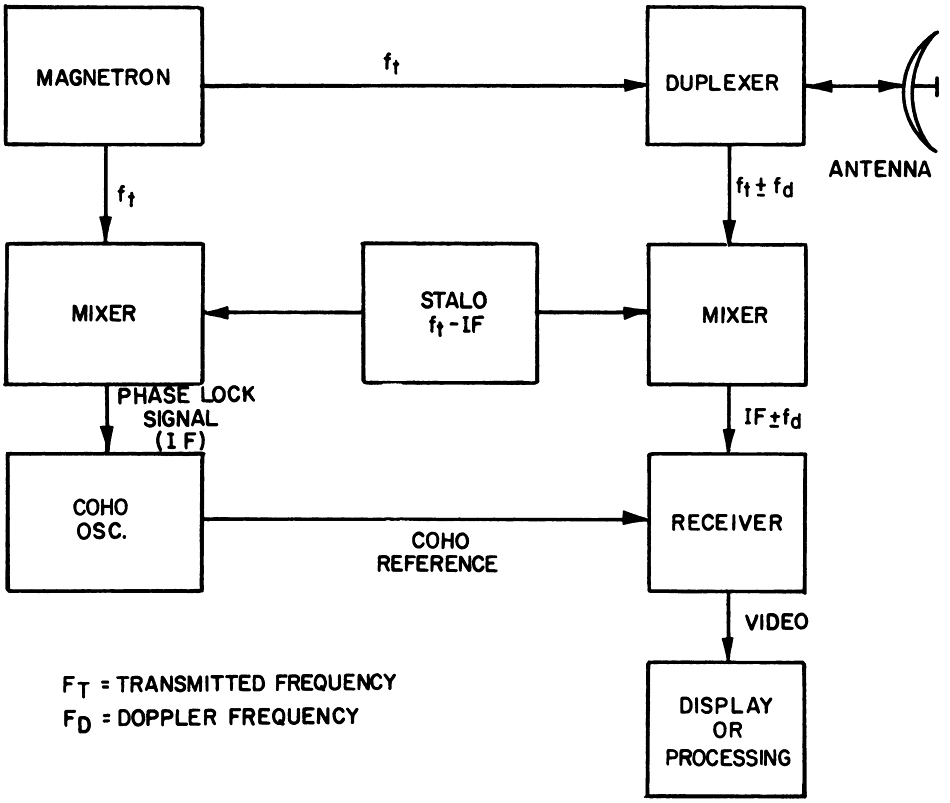

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Figure 4-18.—Coherent MTI with phase-locked COHO oscillator.

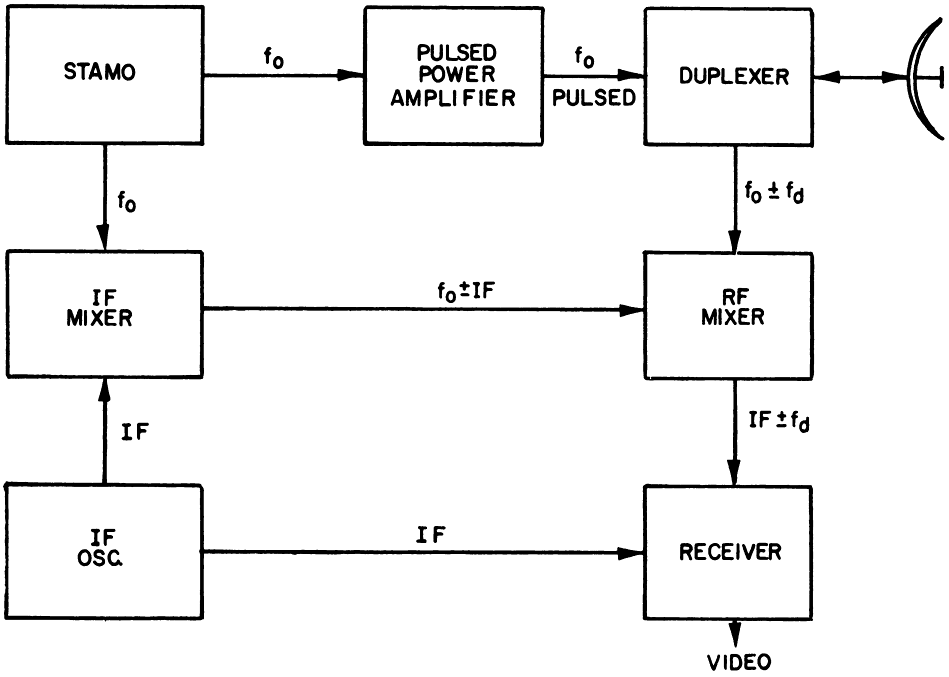

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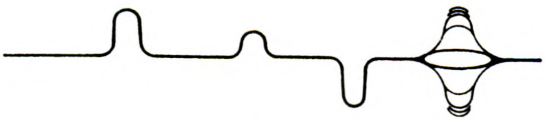
Figure 4-19.—Coherent MTI with STAMO.

discussed later in this topic. Stationary targets produce no Doppler shift; therefore, the return signal echo has the same frequency and phase as the transmitted pulse. A moving target does produce a Doppler shift; therefore, the return signal echo has a different phase from that of the transmitted pulse. To make use of this principle, pulse-Doppler radars must be able to compare the echo signal with a reference signal that is in phase (coherent) with the transmitted signal.

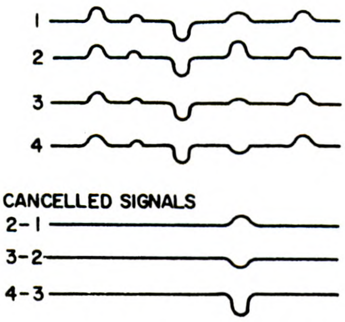
**Coherent Radar Systems.**—A means of storing or controlling the transmitted phase is required to provide coherent detection. One method uses a magnetron (fig. 4-18) for the transmitter. This requires that the local oscillator be stable for a small fraction of a cycle during one pulse period. A sample of the transmitted and stable local oscillator (STALO) signals are fed to the coherent oscillator (COHO). This locks-in the phase of the COHO until the next transmitter pulse.

With the development of power amplifier klystrons, traveling-wave tubes, and crossed-field amplifiers, a much better method evolved for coherency. A pulsed power amplifier (fig. 4-19) fed by a stabilized master oscillator (STAMO) makes up the transmitted signal. The STAMO signal is mixed with the IF oscillator to provide an rf mixer input. The receiver then detects the Doppler shift and produces the video signal. The video signal from either type of coherent radar is usually bipolar (both positive and negative).

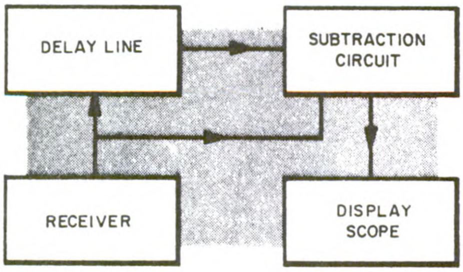
**MTI Radar.**—The bipolar video that is detected in a coherent receiver is caused by the phase and frequency differences of the return signals. A stationary target, such as land, produces the same phase/frequency return each pulse. Moving targets produce changing phase returns each pulse. Figure 4-20, view A, represents the presentation that would be seen on an A scope. It shows three fixed and one moving target in bipolar video for multiple transmissions. The MTI systems use pulse-to-pulse cancellation to suppress the stationary target returns by subtracting the previous return from the current return. In figure 4-20, view B, a series of four returns are shown, followed by three cancelled returns. Superimposing the three sweeps would produce a single target with positive and negative excursions, similar to the moving target in figure 4-20, view A. A basic cancelling system is shown in figure 4-20, view C. The delay line is designed to delay the signal input for the duration of one PRT. The output of the delay line reaches the subtraction circuit at the same time as the next receive interval is applied to the delay line and the subtraction circuit. The subtraction circuit must have both inputs coincident and equal in amplitude so that complete cancellation occurs. The fluctuating returns from moving targets will not cancel. The use of the delay line in the canceller requires a fixed and stable repetition rate because the delay cannot be changed readily. The delay lines used in most MTI radars are supersonic.



A. FIXED AND MOVING TARGETS



B. CANCELLATION OF ECHOES



C. CANCELLING SIGNALS BY SUBTRACTION

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Figure 4-20.—Cancelling echo returns in a MTI radar.

A signal applied travels faster than sound but much slower than the rf velocity in space. Most supersonic delay lines in use have a propagation velocity of about 1,700 feet per second. They use mercury or quartz as the delay medium with some form of transducer to introduce and extract the signal.

With MTI radar systems, the blind velocity problem appears when a fixed PRF is used. When a target moves .5, 1, 1.5, 2, and so forth, wavelengths between consecutive transmitted pulses, the signal return is shifted in 360-degree multiples and produces no phase difference when compared with the COHO signal. These blind velocities (Doppler frequencies) coincide with multiples of the PRF above and below the transmitted frequency. For example, if the PRF is 400 Hz, then Doppler frequencies of ±400, ±800, ±1200, ±1600 Hz and so forth, will be blind velocities.

## TRANSMITTERS

Search and fire control radars require high-powered oscillators and amplifiers to produce the transmitted rf signal. The high-power levels required enable the detection and tracking of targets at extended ranges. Solid state transmitters have only recently been introduced in radar applications. The majority of current radar transmitters still use vacuum tube devices to provide high power rf energy, and will continue to use them for quite some time. The high-power tubes used fall in two categories—crossed field (m) and linear beam (o). Each type has different characteristics that makes one tube more suited for one application than another.

### CROSSED-FIELD TUBES (M TYPE)

Crossed-field tubes get their name from the fact that the dc electric field and magnetic field are crossed (right angles). One of the first crossed-field tubes used in early radars was the magnetron, and it was the only one available for quite a few years. Crossed-field tubes are also known as M-type devices, since they deal with propagation of waves in a magnetic field. There are two types of crossed-field tubes—resonant and nonresonant. The resonant type is an oscillator and the tube itself generates the rf signal. The most common resonant crossed-field tube used in radars is the magnetron. The nonresonant crossed-field tubes are amplifiers and generally will not oscillate, but will amplify an applied rf signal. The amplifiers are subclassed as to whether they use the forward or backward wave and whether or not they are reentrant. (*Reentrant* means whether the electrons emitted by the cathode that return to the cathode can reenter the charge that travels to the anode, or, are then lost [wasted].) Only one type of nonresonant crossed-field tube has found wide use in radar applications—the crossed-field amplifier (CFA). The CFA is nonresonant, backward wave, and reentrant.

#### Magnetrons

Basically, the magnetron is a diode and has no grid. A magnetic field in the space between the plate (anode) and the cathode serves as a grid. The plate of a magnetron does not have the same physical appearance as the plate of an ordinary electron tube. Since conventional LC networks become impractical at microwave frequencies, the plate is fabricated into a cylindrical copper block containing resonant cavities that serve as tuned circuits. The magnetron base differs greatly from the conventional base. It has short, large diameter leads that are carefully sealed into the tube and shielded, as shown in figure 4-21.

The cathode and filament are at the center of the tube. It is supported by the filament leads, which are large and rigid enough to keep the cathode and filament structure fixed in position. The output lead is usually a probe or loop extending into one of the tuned cavities and coupled into a waveguide or coaxial line. The plate structure, as shown in figure 4-22, is a solid block of copper. The cylindrical holes around its circumference are resonant cavities. A narrow slot runs from each cavity into the central portion of the tube and divides the inner structure into as many segments as there are cavities. Alternate segments are strapped together to put the cavities in parallel with regard to the output. These cavities control the output frequency. The straps are circular metal bands that are placed across the top of the block at the entrance slots to the cavities. Since the cathode must operate at high power, it must be fairly large and must be able to withstand

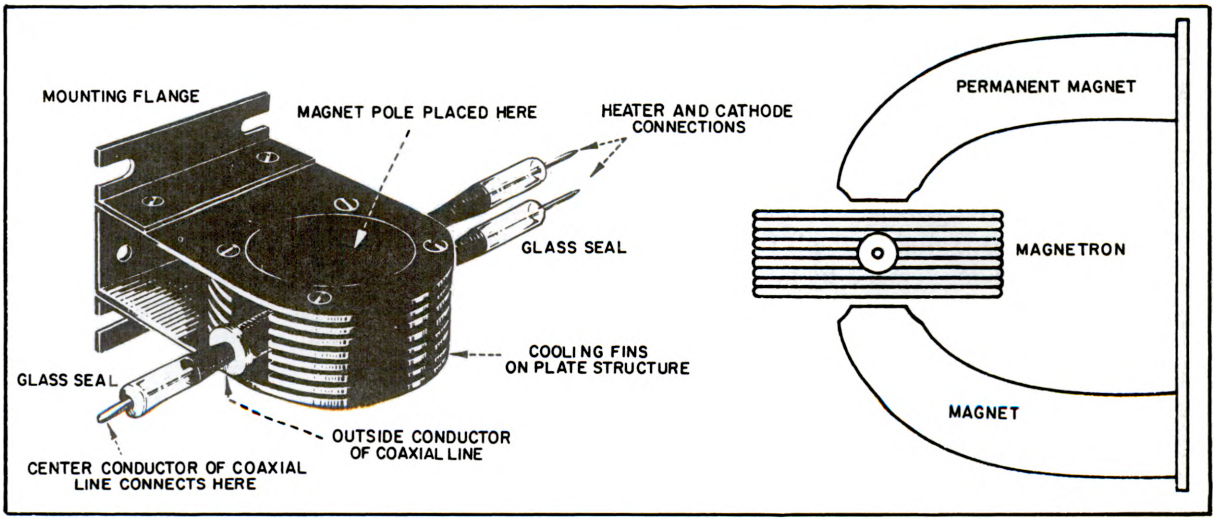
MOUNTING FLANGE
MAGNET POLE PLACED HERE
HEATER AND CATHODE CONNECTIONS
GLASS SEAL
COOLING FINS ON PLATE STRUCTURE
GLASS SEAL
OUTSIDE CONDUCTOR OF COAXIAL LINE
CENTER CONDUCTOR OF COAXIAL LINE CONNECTS HERE
PERMANENT MAGNET
MAGNETRON
MAGNET

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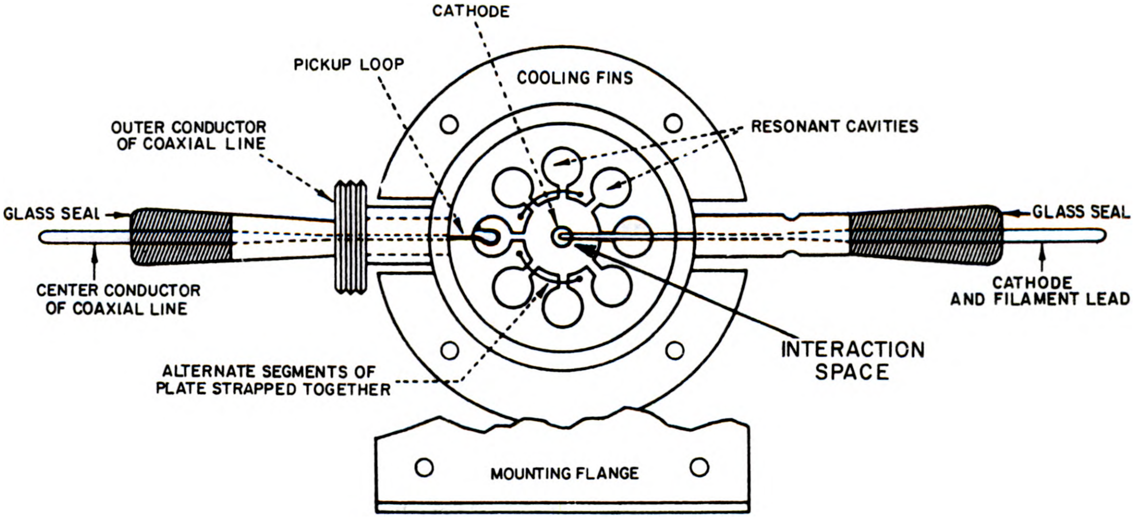
Figure 4-21.—Magnetron.


CATHODE
PICKUP LOOP
COOLING FINS
OUTER CONDUCTOR OF COAXIAL LINE
RESONANT CAVITIES
GLASS SEAL
GLASS SEAL
CENTER CONDUCTOR OF COAXIAL LINE
CATHODE AND FILAMENT LEAD
INTERACTION SPACE
ALTERNATE SEGMENTS OF PLATE STRAPPED TOGETHER
MOUNTING FLANGE

179.702

Figure 4-22.—Cutaway view of a magnetron.

high operating temperatures. It must also have good emission characteristics, particularly under back bombardment, because much of the output power is derived from the large number of electrons emitted when high-velocity electrons return to strike the cathode. The cathode is indirectly heated, and is constructed of a high-emission material. The open space between the plate and the cathode is called the *interaction space*, because it is in this space that the electric and magnetic fields interact to exert force upon the electrons.

The magnetic field is usually provided by a strong, permanent magnet mounted around the magnetron so that the magnetic field is parallel with the axis of the cathode. The cathode is mounted in the center of the interaction space.

The direction of an electric field is from the positive electrode to the negative electrode. The law governing the motion of an electron in an electric (E) field states that the force exerted by an electric field on an electron is proportional to the strength of the field. Electrons tend to move from a point of negative potential toward a positive potential, as shown in figure 4-23. In other words, electrons tend to move against the E field. When an electron is being accelerated by an E field, as shown in figure 4-23, energy is taken from the field by the electrons.

The law of motion of an electron in a magnetic (H) field states that the force exerted on an electron in a magnetic field is at right angles to both the field and the path of the electron. The direction of the force is such that the electron trajectories are clockwise when viewed in the direction of the magnetic field, as shown in figure 4-24.

In figure 4-24, it is assumed that a south pole is below the paper and a north pole is above the paper so that the magnetic field is going into the paper. When an electron is moving in space, a magnetic field is built around the electron just as there would be a magnetic field around a wire when electrons are flowing through a wire. In figure 4-24, note that the magnetic field around the moving electron adds to the permanent magnetic field on the left side of the electron path and subtracts from the permanent magnetic field on the right side of the electron path, thus weakening the field on that side. Therefore, the electron path bends to the right (clockwise). If the permanent magnetic field strength is increased, the electron path will bend sharper. Likewise, if the velocity of the electron increases, the field around it increases, and its path will bend more sharply.

A schematic diagram of a basic magnetron is shown in figure 4-25, view A. The tube consists of a cylindrical plate with a cathode placed coaxially within it. The tuned circuit (not shown) in which oscillations take place are cavities physically located in the plate.

When no magnetic field exists, heating the cathode results in a uniform and direct movement in the field from the cathode to the plate, as

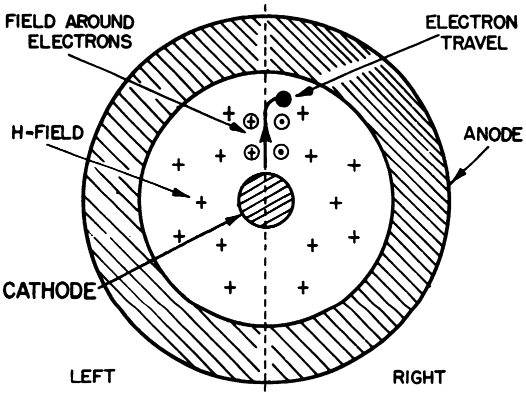


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Figure 4-24.—Electron motion in a magnetic field.

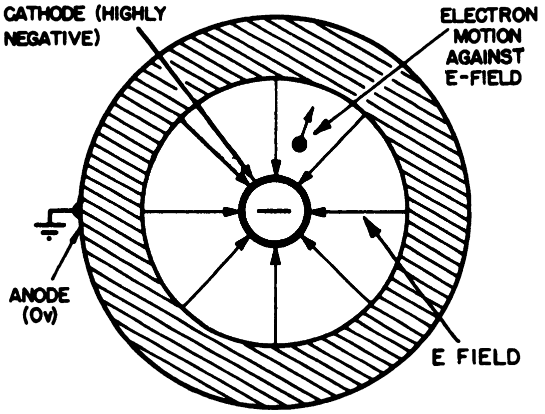

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Figure 4-23.—Electron motion in an electric field.

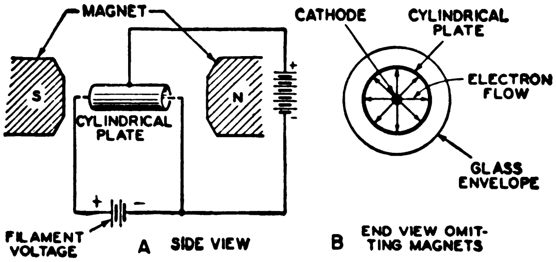

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Figure 4-25.—Basic magnetron.

shown in figure 4-25, view B. However, as the magnetic field surrounding the tube is increased, a single electron is effected, as shown in figure 4-26. In figure 4-26, view A, the magnetic field has been increased to a point where the electron proceeds to the plate in a curve rather than a direct path.

In figure 4-26, view B, the magnetic field has reached a value great enough to cause the electron to just miss the plate and return to the filament in a circular orbit. This value is the CRITICAL VALUE of field strength. In figure 4-26, view C, the value of the field strength has been increased to a point beyond the critical value, and the electron is made to travel to the cathode in a circular path of smaller diameter.

Figure 4-26, view D, shows how the magnetron plate current varies under the influence of the varying magnetic field. In figure 4-26, view A, the electron flow reaches the plate, so there is a large amount of plate current flowing. However, when the critical field value is reached, as shown in figure 4-26, view B, the electrons are deflected away from the plate; and the plate current drops abruptly to a very small value. When the field strength is made still larger, figure 4-26, view C, the plate current drops to zero.

When the magnetron is adjusted to the plate current cutoff or critical value, and the electrons just fail to reach the plate in their circular motion; the magnetron can produce oscillations at microwave frequency by virtue of the currents induced electrostatically by the moving electrons. This frequency is determined by the time it takes the electrons to travel from the cathode toward the plate and back again. A transfer of microwave energy to a load is made possible by connecting an external circuit between the cathode and plate of the magnetron.

Magnetron oscillators are divided into two classes—*negative resistance* and *electron resonance* magnetron oscillators. A *negative resistance* magnetron oscillator operates by reason of a static negative resistance between its electrodes and has a frequency equal to the natural period of the tuned circuit connected to the tube. An *electron resonance* magnetron oscillator operates by reason of the electron transit time characteristics of an electron tube; that is, the time it takes electrons to travel from cathode to plate. This oscillator is capable of generating very large peak power outputs at frequencies in the thousands of megahertz. Although its average power output over a period of time is low, it can put out very high-power oscillations in short bursts of pulses.

The split-anode negative resistance magnetron is a variation of the basic magnetron, which operates at a higher frequency and is capable of more output. Its general construction is similar to the basic magnetron, except that it has a split plate, as shown in figure 4-27. These half plates are operated at different potentials to provide an electron

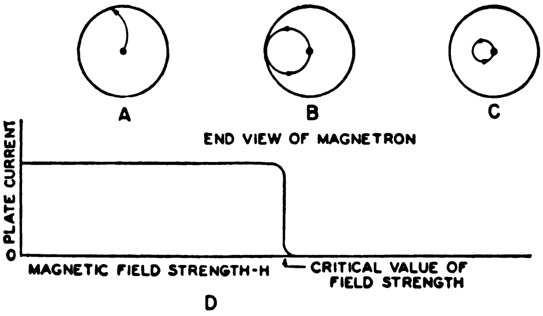

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Figure 4-26.—Effect of magnetic field on single electron.

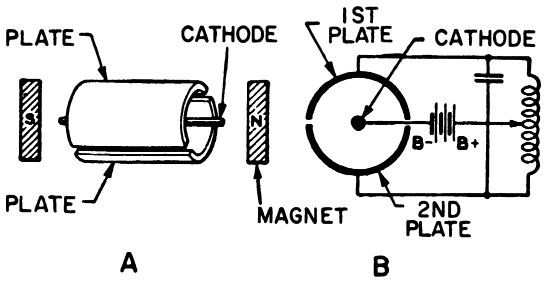

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Figure 4-27.—Split-anode magnetron and its output.

motion, as shown in figure 4-28. The electron leaving the cathode and progressing toward the high potential plate is deflected by the magnetic field at a certain radius of curvature. After passing the split between the two plates, the electron enters the electrostatic field set up by the lower potential plate. Here the magnetic field has more effect on the electron, which is deflected at a smaller radius of curvature. The electron then continues to make a series of loops through the magnetic field and electric field until it finally falls on the low potential plate.

Oscillations can be started by applying the proper value of magnetic field to the tube. The value of field required is somewhat beyond the critical value, which, for the split-anode tube, is the field required to cause all the electrons to miss the plate when its halves are operating at the same potential. However, the alternating voltages impressed on the plates as a result of the oscillation generated in the tank circuit will cause electron motion, such as that shown in figure 4-28, and current will flow. Since a very concentrated magnetic field is required for the negative resistance magnetron oscillator, the length of the tube plate is limited to a few centimeters for a magnet of reasonable dimensions. In addition, a small diameter tube is required to make the magnetron operate efficiently at microwave frequencies. For this reason, a heavy-walled plate is used to increase the heat radiation properties of the tube. To obtain still greater dissipation, tubes with high outputs use an artificial cooling method, such as forced air or water cooling.

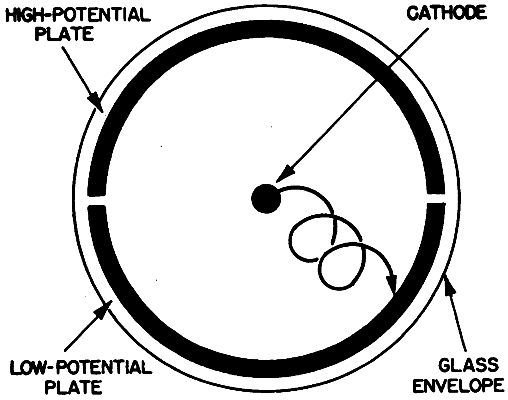

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Figure 4-28.—Movement of electron in a split-anode magnetron.

The output of magnetrons is somewhat reduced by the bombardment of the filament by electrons that travel in loops (fig. 4-26, views B and C). This effect causes an increase of filament temperature under certain conditions of high magnetic field and high plate voltage, and sometimes results in unstable operation of the tube. The effects of filament bombardment can be compensated for by operating the filament at reduced voltage. In some cases, the plate voltage and field strength also are reduced to prevent destructive filament bombardment.

In the electron resonance type of magnetron, the plate itself may be so constructed as to resonate and function as a tank circuit. Thus, there are no external tuned circuits; power is delivered directly from the tube to a transmission line, as shown in figure 4-29. The tube constants and operating conditions are such that the electron paths are somewhat different from those in figure 4-28. Instead of having closed spirals or loops, the path is a curve having a series of abrupt points, as shown in figure 4-30. Ordinarily, this type of magnetron also has more than two segments in the plate. For example, figure 4-30 shows an eight-segment plate.

This type of magnetron is the most widely used at present for microwave frequencies. Modern designs have a reasonably high efficiency and relatively high output. However, one disadvantage of the electron resonance magnetron is that its average power is limited by the cathode emission. Furthermore, the peak power is limited by the maximum voltage that it can withstand without injury. Three common types of anode

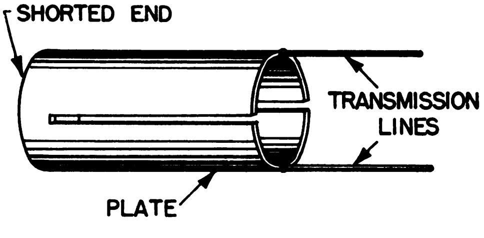

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Figure 4-29.—Plate tank circuit of magnetron.

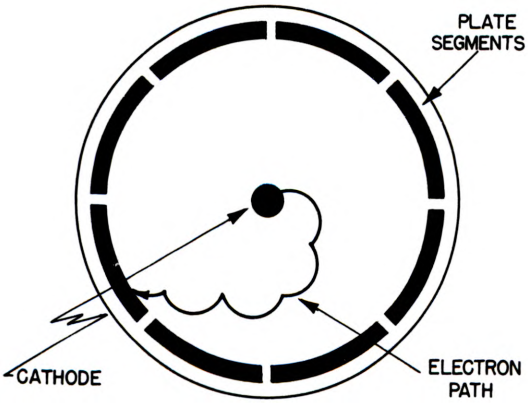

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**Figure 4-30.—Electron path in electron resonance magnetron.**

blocks used in electron resonance magnetrons are shown in figure 4-31.

The first type, shown in figure 4-31, has cylindrical cavities. This type is called a *hole-and-slot anode*. The second type is called the *vane anode*, which has trapezoidal cavities. These first two anode blocks operate in such a way that alternate segments must be connected, or strapped, to ensure that each segment is opposite in polarity to its neighboring segment on either side, as shown in figure 4-32. This also requires an even number of cavities.

The third type, shown in figure 4-31, is called a *rising sun anode* because of its appearance. The alternate large and small trapezoidal cavities in this block result in a stable frequency between the resonant frequencies of the large and the small cavities.

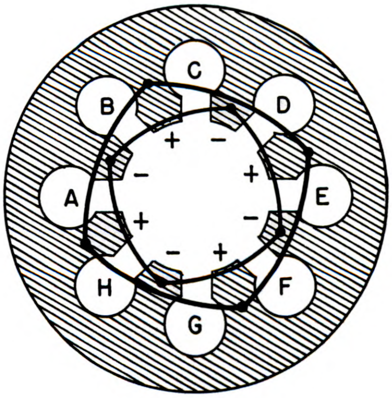

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**Figure 4-32.—Strapping alternate segments.**

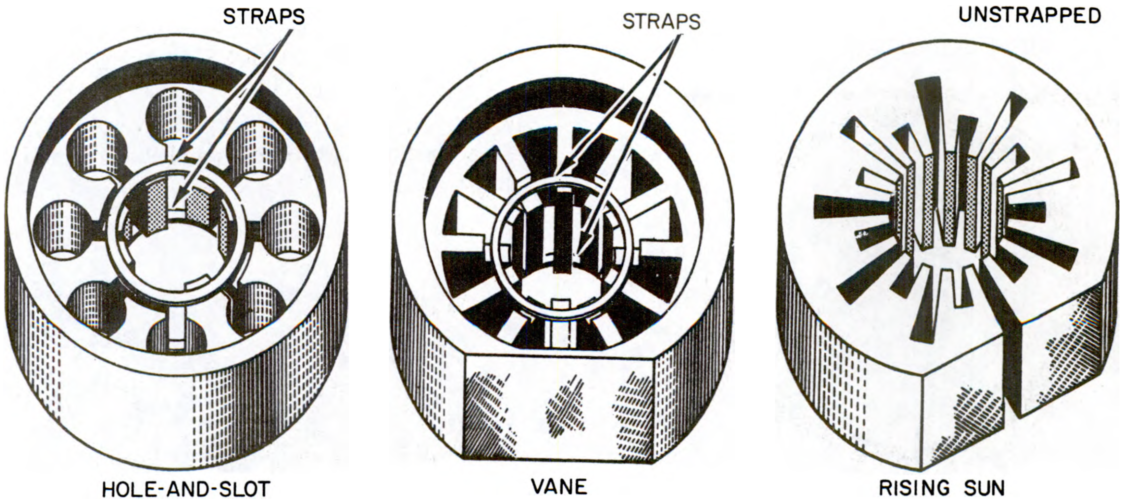

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**Figure 4-31.—Common types of anode blocks.**

Figure 4-33, view A, shows the physical appearance of the resonant cavities contained in the hole-and-slot anode that we will use when analyzing the operation of the electron resonance magnetron. Notice that the cavity consists of a cylindrical hole in the copper anode and a slot that connects the cavity to the interaction space.

The electrical equivalent circuit of the cavity and slot is shown in figure 4-33, view B. The parallel sides of the slot form the plates of a capacitor, while the walls of the hole act as an inductor. The hole and slot thus form a high Q resonant LC circuit. As shown in figure 4-31, the anode of a magnetron contains a number of these cavities.

An analysis of the anode in figure 4-31 reveals that the LC tank of each cavity is in series, as shown in figure 4-34. This is assuming the straps have been removed. However, an analysis of the anode block after alternate segments have been strapped (fig. 4-32) reveals that the cavities are now connected in parallel. This is due to the strapping. The result is shown in figure 4-35.

**OPERATION.**—The electric field in the electron resonant oscillator is a product of an ac and a dc field. The dc field extends radially between adjacent anode segments by the rf oscillations induced in the cavity tank circuits of the anode block.

Figure 4-36 shows the ac fields between adjacent segments at an instant of maximum magnitude of one alternation in the rf oscillations occurring in the cavities. The strong dc field going from anode to cathode, due to a large negative dc voltage pulse applied to the cathode, is not shown in figure 4-36, but it is assumed to be present (it was shown in fig. 4-23). It is

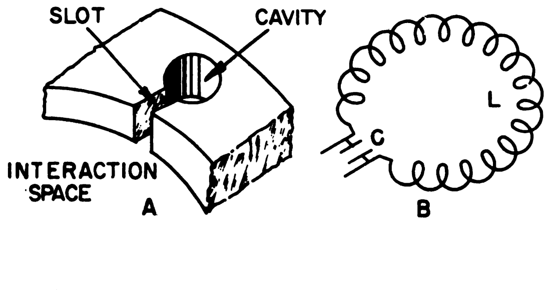

Figure 4-33.—Equivalent circuit of a hole-and-slot cavity.

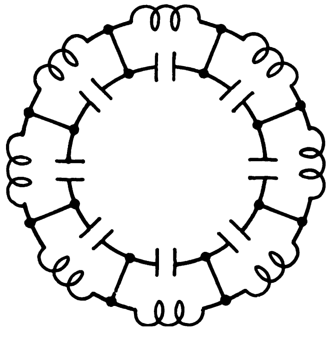

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Figure 4-34.—Cavities connected in series.

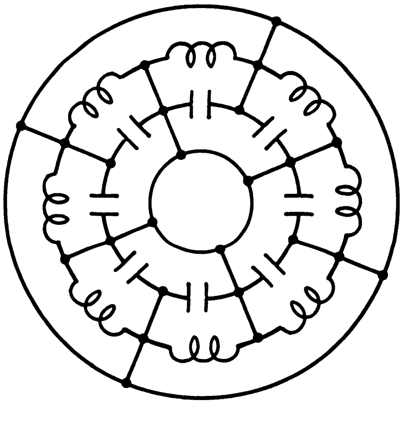

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Figure 4-35.—Cavities in parallel due to strapping.

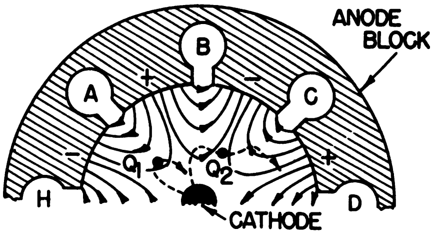

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Figure 4-36.—Electron paths in an electron resonant magnetron oscillator—rf oscillations occurring.

actually this strong dc field that causes electrons to accelerate toward the plate after they have been emitted from the cathode. Earlier in this chapter, it was pointed out that an electric field went from a positive electrode to a negative electrode. Also, an electron moving against an E field would be accelerated by the field, thus taking energy from the field. An electron would give up energy to a field and slow down if it were moving in the same direction as the field (positive to negative). Oscillations are sustained in a magnetron because electrons gain energy from the dc field. Electrons give up this energy to the ac fields as they pass through these fields. These electrons are sometimes referred to as *working electrons*. However, not all of the electrons give up energy to the ac fields. Some electrons may actually take energy from the ac fields. This action is undesirable.

In figure 4-36, consider electron Q1, which is shown entering the field around the slot entrance to cavity A. The clockwise rotation of the electron path is due to the interaction of the magnetic field around the moving electron with the permanent magnetic field, which is assumed to be going into the paper in figure 4-36. The action of an electron moving in an H field was explained earlier and shown in figure 4-24. Notice that electron Q1, which has entered the ac field around cavity A, is going against this ac field. Thus, it will take energy from the ac field and be accelerated. The electron will turn more sharply when its velocity increases, as was explained earlier. Thus, electron Q1 will turn back toward the cathode. When it strikes the cathode, it will give up the energy it received from the ac field in the form of heat. This will also force more electrons to leave the cathode and accelerate toward the anode. Electron Q2 is, therefore, slowed down by the field and gives up some of its energy to the ac field. Since electron Q2 looses velocity, the deflective force exerted by the H field is reduced and the electron path deviates to the left in the direction of the anode, rather than return to the cathode as did electron Q1.

The cathode-to-anode potential and the magnetic field strength (E-field to H-field relationship) determines the time taken by electron Q2 to travel from a position in front of cavity B to a position in front of cavity C. Cavity C is equal to approximately one-half cycle of the rf oscillation of the cavities. When electron Q2 reaches a position in front of cavity C, the ac field of cavity C will be reversed from that shown.

Therefore, electron Q2 will give up energy to the ac field of cavity C and will slow down more. Electron Q2 will actually give up energy to each cavity as it passes, and it will eventually reach the anode when its energy is expended. Thus, electron Q2 will have helped sustain oscillations because it has taken energy from the dc field and given it to the ac fields. Electron Q1, which took energy from the ac field around cavity A, did little harm because it immediately returned to the cathode.

Electrons, such as electron Q2, that give up energy to the ac field as they rotate clockwise from one ac field to the next are called *working electrons*. They stay in the interaction space for a considerable time before striking the anode.

The cumulative action of many electrons being returned to the cathode and directed toward the anode forms a pattern resembling the spokes of a wheel, as indicated in figure 4-37. Electrons in the spokes of the wheel are the working electrons.

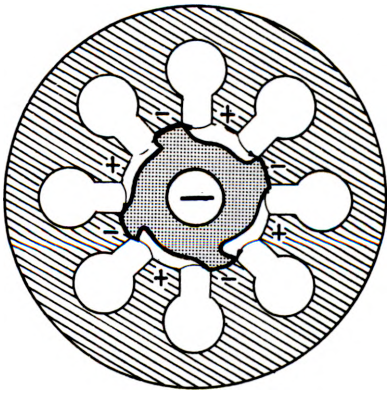

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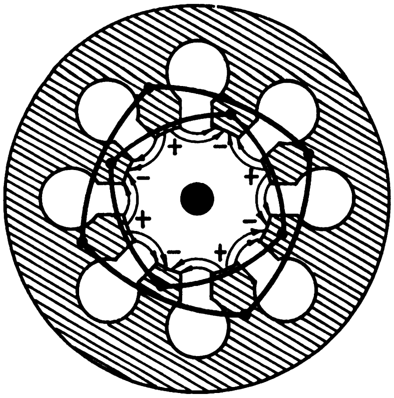
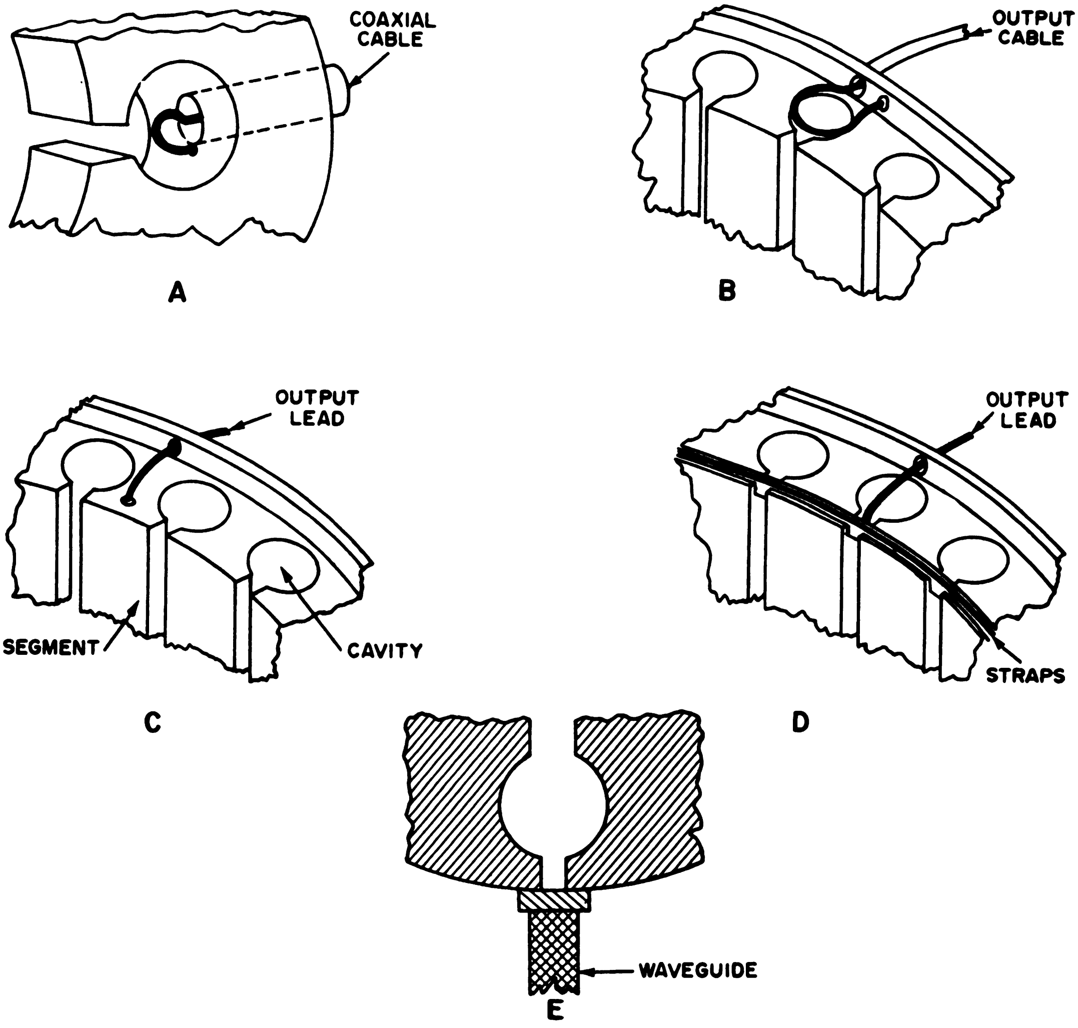
**Figure 4-37.—Rotating space charge wheel in eight cavity magnetron.**



179.716
Figure 4-38.—Alternate segments connected by strapping rings.

This overall space charge wheel rotates about the cathode at an angular velocity of two poles (anode segments) per cycle of the ac field and of a phase that enables the concentration to continuously deliver energy to sustain the rf oscillations. As previously explained, electrons emitted from the area of the cathode between the spokes are quickly returned to the cathode.

In figure 4-37, it is assumed that alternate segments between cavities are at the same potential at the same instant, and there is an ac field existing across each individual cavity. This type of mode of operation is called the *pi mode*, since adjacent segments of the anode have a phase difference of 180° or 1-pi radian.



179.717
Figure 4-39.—Magnetron coupling methods.

There are several other possible modes of oscillation.

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A magnetron operated in the pi mode has greater power output. Therefore, the pi mode is the most commonly used mode.

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To ensure that alternate segments have identical polarities, an even number of cavities, usually six or eight, are used and alternate segments are strapped, as pointed out earlier. The frequency of the pi mode is separated from the frequency of the other modes by strapping.

For the pi mode, all parts of each strapping ring are at the same potential, but the two rings have alternately opposing potentials, as shown in figure 4-38. Stray capacitance between the rings adds capacitive loading to the resonant mode. For other modes, however, there is a phase difference between the successive segments connected to a given strapping ring that causes current to flow in the straps. The straps contain inductance; therefore, an inductive shunt is placed in parallel with the equivalent circuit, thereby lowering the inductance and increasing the frequency at modes other than the pi mode.

**COUPLING METHODS.**—The rf energy can be removed from a magnetron by means of a coupling loop. At frequencies lower than 10,000 MHz, the coupling loop is made by bending the inner conductor of a coaxial cable into a loop and soldering the end to the outer conductor so that the loop projects into the cavity, as shown in figure 4-39, view A. To obtain sufficient pickup at higher frequencies, the loop is located at the end of the cavity, as shown in figure 4-39, view B.

The segment-fed loop method is shown in figure 4-39, view C. The loop intercepts the flux passing between cavities. The strap-fed loop method (fig. 4-39, view D) intercepts the energy between the strap and the segment. On the output side, the coaxial line feeds another coaxial line directly, or it feeds a waveguide through a choke joint, with the vacuum seal at the inner conductor helping to support the line.

Aperture, or slot, coupling is shown in figure 4-39, view E. Here, energy is coupled directly to a waveguide through an iris feeding into the waveguide connector through a window.

**TUNING.**—A tunable magnetron permits the system to be operated at a precise frequency anywhere within a band of frequencies, as determined by the magnetrons characteristics.

The resonant frequency of a magnetron may be varied by varying the inductance or capacitance of the resonant cavities. In figure 4-40, an inductive tuning element is inserted into the hole portion of the hole-and-slot cavities. It changes the inductance of the resonant circuits by altering the surface-to-volume ratio in a high-current region. This type of tuner, shown in figure 4-40, is called a *sprocket tuner* or *crown-of-thorns* tuner. All of its tuning elements are attached to a frame, which is positioned by means of a flexible bellows arrangement. The insertion of the tuning elements into each anode hole decreases the inductance of the cavity; therefore, the resonant frequency is increased. One of the limitations of inductive tuning is that it lowers the unloaded Q of the cavities and, therefore, reduces the efficiency of the tube.

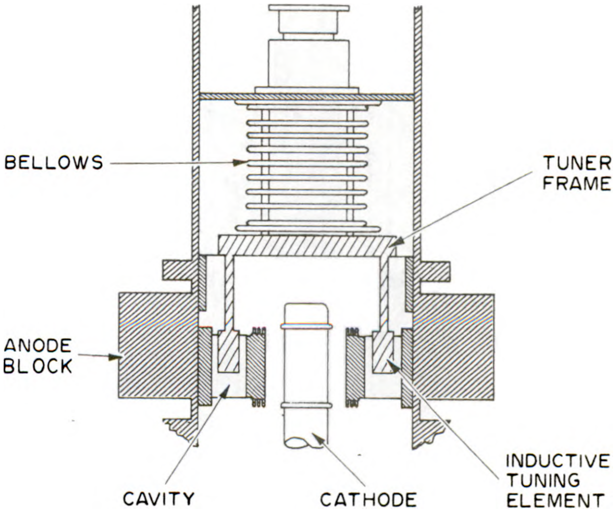

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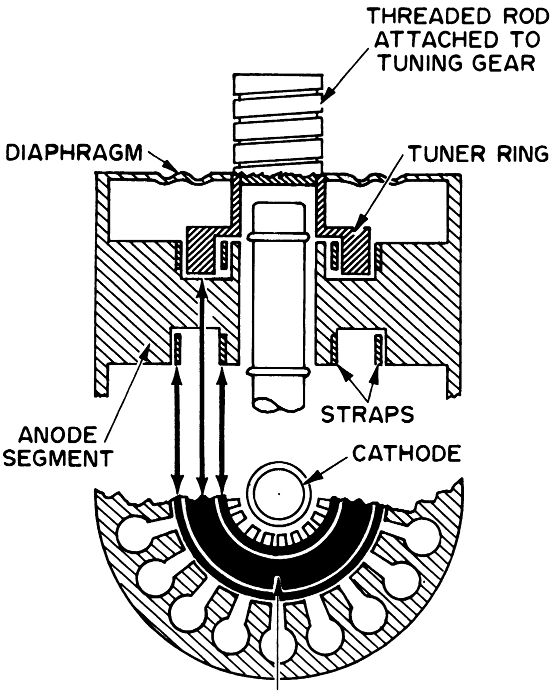
**Figure 4-40.—Inductive magnetron tuning.**

The insertion of an element (ring) into the cavity slot, as shown in figure 4-41, increases the slot capacitance and decreases the resonant frequency. Because the gap is narrowed in width, the breakdown voltage will be lowered. The capacity tuned magnetrons must be operated with low voltages and hence low powers. The type of capacity tuner shown in figure 4-41 is called a ***cookie-cutter tuner***. It consists of a metal ring inserted between the two rings of a double-strapped magnetron, thereby increasing the strap capacitance. Because of the mechanical and voltage breakdown problems associated with the cookie-cutter tuner, it is more suited for use at longer wavelengths.

Both the capacitance and inductance tuners described above are symmetrical. Each cavity is affected in the same manner, and the angular symmetry of the pi mode is preserved.

A 10-percent frequency range may be obtained with either of the two tuning methods described above. There is some indication that the cookie cutter is more restricted than the crown-of-thorns tuner. The two tuning methods may be used in combination to cover a larger tuning range than is possible with either one alone.



WIDE LINE REPRESENTS TUNER-RING POSITION BETWEEN THE MEGNETRON STRAPS

179.719

**Figure 4-41.—Capacitive magnetron tuning.**

**SEASONING.**—During initial operation, a high-power magnetron arcs from cathode to plate and must be properly ***broken in*** or ***baked in***. Actually, arcing in magnetrons is very common. It occurs with a new tube or following long periods of idleness.

One of the prime causes of arcing is the liberation of gas from tube elements during idle periods. Arcing may also be caused by the presence of sharp surfaces within the tube, mode shifting, and by drawing excessive current. While the cathode can withstand considerable arcing for short periods of time, continued arcing will shorten the life of the magnetron and may destroy it entirely. Hence, each time excessive arcing occurs, the tube must be baked in again until the arcing ceases and the tube is stabilized.

The baking-in procedure is relatively simple. Magnetron voltage is raised from a low value until arcing occurs several times a second. The voltage is left at that value until arcing dies out. Then, the voltage is raised further until arcing again occurs, and it is left at that value until the arcing again dies out. Whenever the arcing becomes very violent and resembles a continuous arc, the applied voltage is excessive and should be reduced to permit the magnetron to recover. When normal rated voltage is reached and the magnetron remains stable at the rated current, the baking in is complete. It is good maintenance practice to bake in magnetrons left idle in the equipment, or those used as spares, when long periods of nonoperating time have accumulated.

The preceding information is general in nature. The equipment technical manuals recommended times and PMS procedures should be followed when baking in a specific type of magnetron.

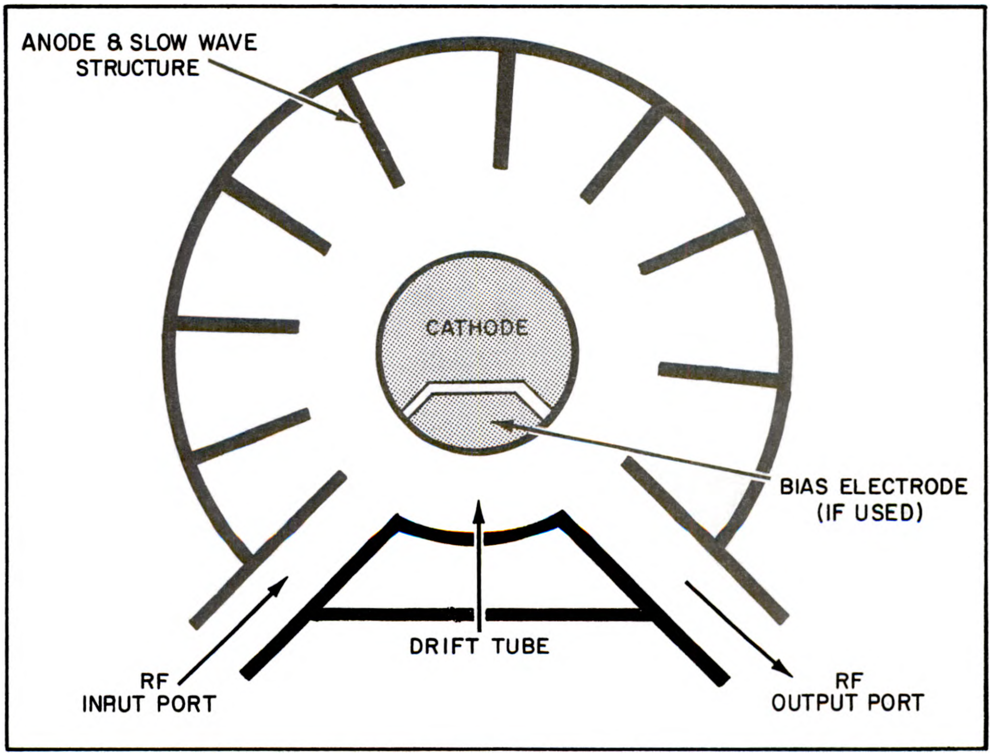
### Crossed-Field Amplifier (CFA)

The CFA is constructed very similar to a magnetron. The major difference is that the CFA requires an rf input in addition to the electrical input and magnetic field. Figure 4-42 shows the construction of a typical CFA.

The CFA anode is very similar to that of a regular trapezoid block magnetron, with the exception of the drift tube section. The drift tube section (fig. 4-42) serves two purposes; (1) to dampen out electron bunches, and thus oscillations as the spokes move past the output port, and (2) to provide a path for rf energy from the input to the output. The CFA is normally used in a chain of two or more CFAs in series. When the CFA is not pulsed with high voltage, the tube presents a low impedance to input rf and passes it through to the output port. When used in a chain, one or more CFAs can be energized, depending on the output power required. For example, for close-in targets, the final stage or stages may not be needed, but all CFAs are required for detection of small targets at maximum range.

The cathode of a CFA is cylindrical just as in magnetrons, however, most are "cold" cathodes (no filaments or heaters). With a cold cathode, sufficient electron emission is available to form a space charge when an electric field is applied. The electrons will not achieve sufficient velocity to escape the region close to the cathode without an rf field applied. Initially, when an rf field is applied, the electrons gain some energy from the rf and move farther out from the cathode. Some will gain even more energy and reach the anode. Others will return to the cathode and strike with sufficient energy to cause secondary emission and increase the electrons in the space charge. Therefore, the major source of electrons is secondary emission from the reentrant electrons.

Secondary emission generates heat in the cathode and further increases emission. If the cathode becomes too hot, thermionic emission may become sufficient to allow the tube to oscillate or produce noise even though an rf field is not applied. To prevent the spurious generation of noise, the cathode is usually water cooled. Another means of reducing noise output is to make the rf pulse slightly wider than the



55.403

Figure 4-42.—Crossed field amplifier (CFA).

high-voltage pulse. Further control is found on some tubes with a bias electrode (fig. 4-42) sometimes called a cutoff electrode. The bias electrode has a positive pulse (positive with respect to the cathode) applied just before the end of the rf pulse. The cutoff pulse allows the electrode to collect the electrons in the drift tube region and the tube to shut off. The pulse must be wide enough to extend past the end of the rf pulse.

CFAs do not have the gain of some of the linear-beam tubes. However, when used in a multistage chain, they can produce equal or greater overall gain at lower high-voltage requirements than a linear-beam amplifier such as a multicavity klystron. For example, a typical CFA can deliver a 1 MW rf peak power output with about a 40 kV, 50-ampere peak pulse, where a klystron would require a 90 kV, 40-ampere peak pulse to produce the same rf output. However, the CFA would require a higher power level input drive signal than the klystron. Another advantage of the CFA is the cold cathode, which normally has a much longer operating life than a heated cathode. A third advantage is the CFAs produce far less X-rays than linear-beam tubes; therefore, lead shielding is not required.

## LINEAR-BEAM TUBES (O TYPE)

A linear-beam tube uses a magnetic field that is parallel to the electron beam and is used to focus the beam. Some tubes do not use a magnetic field; instead, electrostatic focusing is used to hold the beam together while it travels the length of the tube. The two most common types of linear-beam tubes used in fire control equipment is discussed here. The two types of tubes are the klystron and the traveling-wave tube (TWT).

### Klystron Amplifiers

The basic theory of a klystron amplifier is quite simple. The klystron amplification principle may be readily explained with an analogy to a simple triode amplifier with tuned plate and grid circuits.

Figure 4-43 shows a simplified schematic of a triode amplifier with resonant circuits at both the input and output. Such resonant circuits restrict the bandwidth of the amplifier and increase the gain. Reviewing, a triode tube consists of three elements: a cathode that emits a stream of electrons, a grid that controls the electron stream, and a plate that attracts the electrons and catches them after they pass through the grid. The grid acts as a valve, opening or closing the current path according to the voltage applied to it. The rf input signal comes to the grid as a weak alternating voltage. This voltage modulates the electron flow through the tube at the radio frequency. The electron stream then delivers, at the plate, an alternating current, which is an amplified reproduction of the input signal. This alternating current flows through the resonant plate circuit and excites alternating voltages across it. These voltages constitute the rf output from the amplifier.

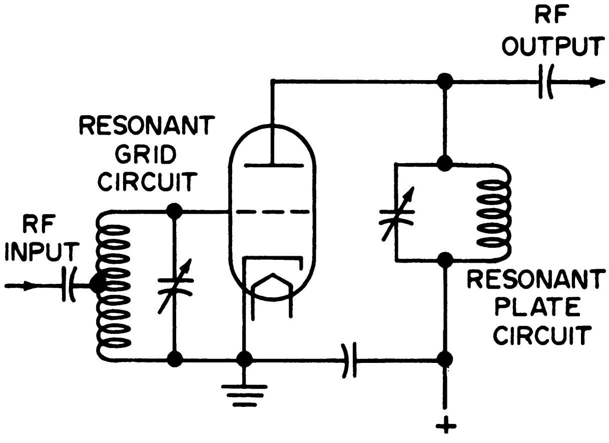


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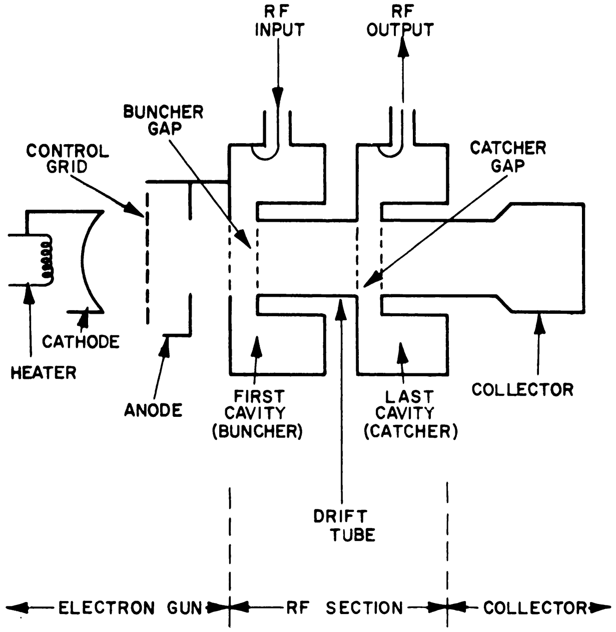
**Figure 4-43.—Simplified schematic of a triode amplifier with resonant circuits of both input and output (TPTG).**

The time it takes electrons to cross the tube is on the order of a billionth of a second. This transit time is short compared to the period of a cycle of a radio wave below the microwave range (approximately a millionth of a second). Hence, the electrons are slowed down or speeded up by the voltage on the grid at a given instant. The flow of electrons, therefore, can follow the voltage fluctuation on the grid. In the case of microwaves, however, the oscillations are so rapid (that is, the period of a cycle is so short) that the voltage on the grid may go through several complete oscillations while a particular quantity of electrons travel across the tube. In other words, the grid voltage changes too rapidly for the electrons to follow the fluctuation. There are other reasons why the conventional triode tube fails at microwave frequencies, but the most fundamental reason is the transit time of the electrons is long compared to the period of one cycle of the microwave signal.

The klystron tube makes a virtue of the very thing that defeats the triode—the transit time of the electrons. The klystron modulates the velocity of the electrons, so that as the electrons travel through the tube, electron bunches are formed. These bunches deliver an oscillating current to the output resonant circuit of the klystron. Figure 4-44 shows a cutaway representation of a basic klystron amplifier. The klystron amplifier consists of three separate sections: the electron gun, the rf section, and the collector.

Consider first the electron gun structure. It consists of a heater, cathode, control grid, and anode. Electrons are emitted by the cathode and drawn toward the anode, which is operated at a positive potential with respect to the cathode. The electrons are formed into a narrow beam by either electrostatic or magnetic focusing techniques (not shown). The control grid is used to control the number of electrons that reach the anode region. It may also be used to turn the tube completely on or off in certain pulsed amplifier applications.



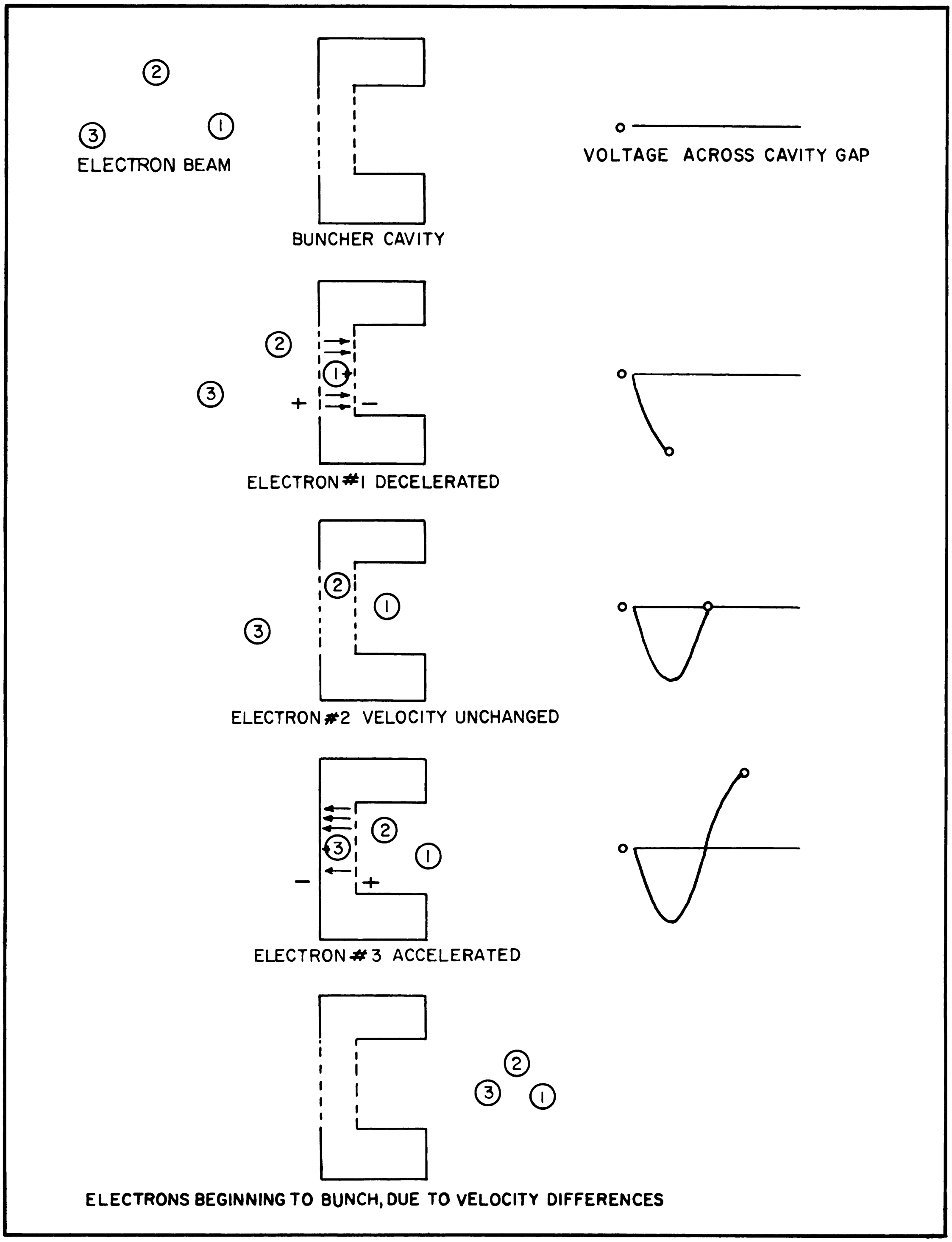
32.82(179)A

**Figure 4-44.—Cutaway representation of a basic klystron amplifier.**

The electron beam is well formed by the time it reaches the anode. The beam passes through a hole in the anode and on to the rf section of the tube, and eventually it strikes the collector. The electrons are returned to the cathode through an external power supply (not shown in figure 4-44). It is evident that the collector of a klystron acts much like the plate of a triode insofar as the collecting of electrons is concerned. However, there is one important difference. The plate of a triode is normally connected, in some fashion, to the output rf circuit, whereas, in a klystron amplifier, the collector has no connection to the rf circuitry at all.

Consider the rf section of a basic klystron amplifier. This part of the tube is quite different from a conventional triode amplifier. The resonant circuits used in a klystron amplifier are reentrant cavities. The characteristics of this type of cavity have been discussed previously.

Referring to figure 4-44, electrons pass through the cavity gaps in each of the resonators as well as the cylindrical metal tube between the gaps. These metal tubes are called ***drift tubes***. In a klystron amplifier, the low-level rf input signal is coupled to the first resonator, which is called the ***input (buncher) cavity***. The signal may be coupled through either a waveguide or a coaxial connection. If the cavity is tuned to the frequency of the rf input, it will be excited into oscillation. An electric field will exist across the buncher gap, alternating at the input frequency. For half a cycle, the electric field will be in a direction that causes the field to increase the velocity of electrons flowing through the gap. On the other half of the cycle, the field will be in a direction that causes the field to decrease electron velocity. This


②
③ ①
ELECTRON BEAM
BUNCHER CAVITY
VOLTAGE ACROSS CAVITY GAP
②
① 
③
+
−
ELECTRON #1 DECELERATED
②
① 
③
ELECTRON #2 VELOCITY UNCHANGED
②
③
①
−
+
ELECTRON #3 ACCELERATED
②
③ ①
ELECTRONS BEGINNING TO BUNCH, DUE TO VELOCITY DIFFERENCES

179.721

Figure 4-45.—Velocity modulation.

effect is called *velocity modulation*, and it is shown in figure 4-45.

NOTE: When the voltage across the cavity gap is negative, electrons decelerate; when the voltage is zero, the electrons are unaffected; and when the voltage is positive, the electrons accelerate.

After leaving the buncher gap (fig. 4-45), the electrons proceed through the drift tube region toward the collector. In the drift tube region, electrons that have been speeded up by the electric field in the buncher gap tend to overtake electrons that have been slowed down. Because of this action, bunches of electrons begin to form in the drift tube region and will be completely formed by the time they reach the gap of the last cavity. The last cavity is called the *output (catcher) cavity*. Bunches of electrons periodically flow through the gap of this output cavity, and during the time between bunches, relatively few electrons flow through the gap. The time between arrival of electron bunches is equal to the period of one cycle of the rf input signal.

The initial bunch of electrons flowing through the catcher cavity cause the cavity to oscillate at its resonant frequency. This sets up an alternating electric field across the catcher cavity gap, as shown in figure 4-46.

With proper design and operating potentials, a bunch of electrons will arrive in the output cavity gap at the proper time to be retarded by the rf field. Thus, energy will be given up to the catcher cavity. This action is shown in figure 4-47.

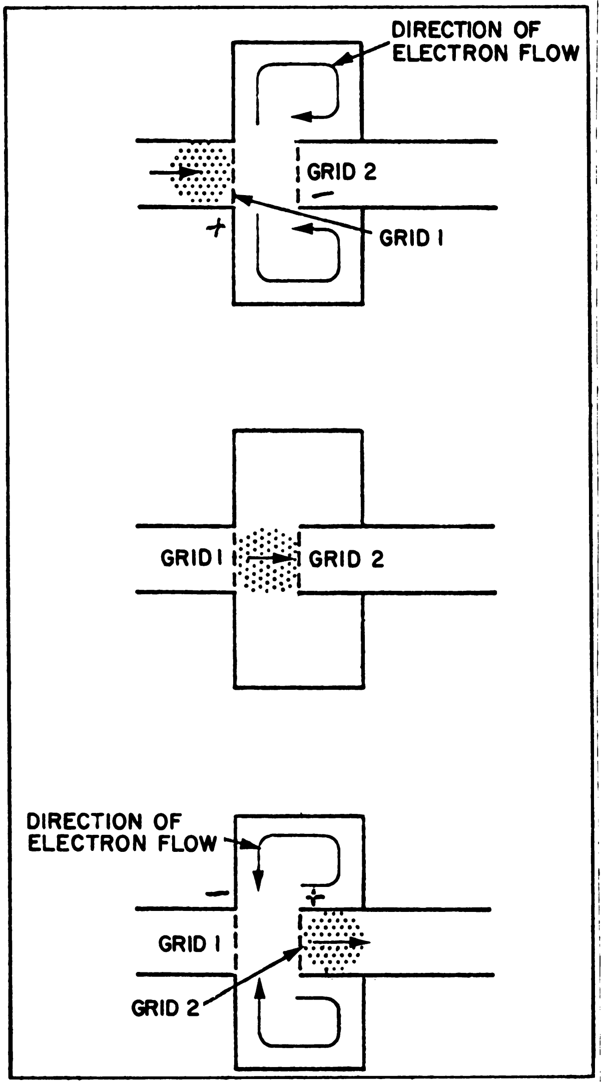


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Figure 4-46.—Catcher cavity gap alternating electric field.

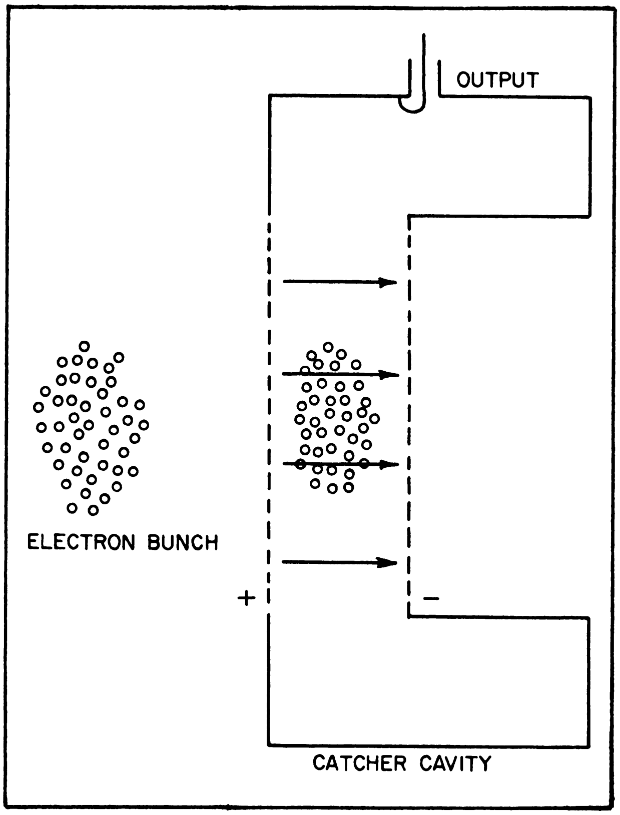

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Figure 4-47.—Electron bunch arriving in output (catcher) cavity gap at the proper time to be retarded in the RF field.

The rf power in the output cavity is much greater than that applied in the buncher cavity. This is due to the ability of the concentrated bunches of electrons to deliver great amounts of energy to the catcher cavity. Since the electron beam delivers some of its energy to the output cavity, it arrives at the collector with less total energy than it had when it passed through the input cavity. This difference in beam energy is approximately equal to the energy delivered to the output cavity.

It is appropriate to mention here that velocity modulation does not form perfect bunches of electrons. Some electrons are out of phase and show up in the output cavity gap between bunches. The electric field across the gap at the time these out-of-phase electrons come through is in a direction to accelerate them. This causes some energy to be taken from the cavity. However, much more energy is contributed to the output cavity by the concentrated bunches of electrons than are withdrawn from it by the small number of out-of-phase electrons.

**MULTICAVITY POWER KLYSTRON AMPLIFIER.**—In the above discussion, only a basic two-cavity klystron has been considered. This simple type of klystron amplifier is not capable of high gain, high output power, or suitable efficiency. With the addition of intermediate cavities and other physical modifications, the basic two-cavity klystron may be converted to a multicavity power klystron. This amplifier is capable of high-gain and high-power output. Figure 4-48 shows a multicavity power klystron amplifier.

In addition to the intermediate cavities, there are several physical differences between the basic and the multicavity klystron. The cathode of the multicavity power klystron must be larger to be capable of emitting large numbers of electrons. The shape of the cathode is usually concave; this aids in focusing the electron beam. The collector

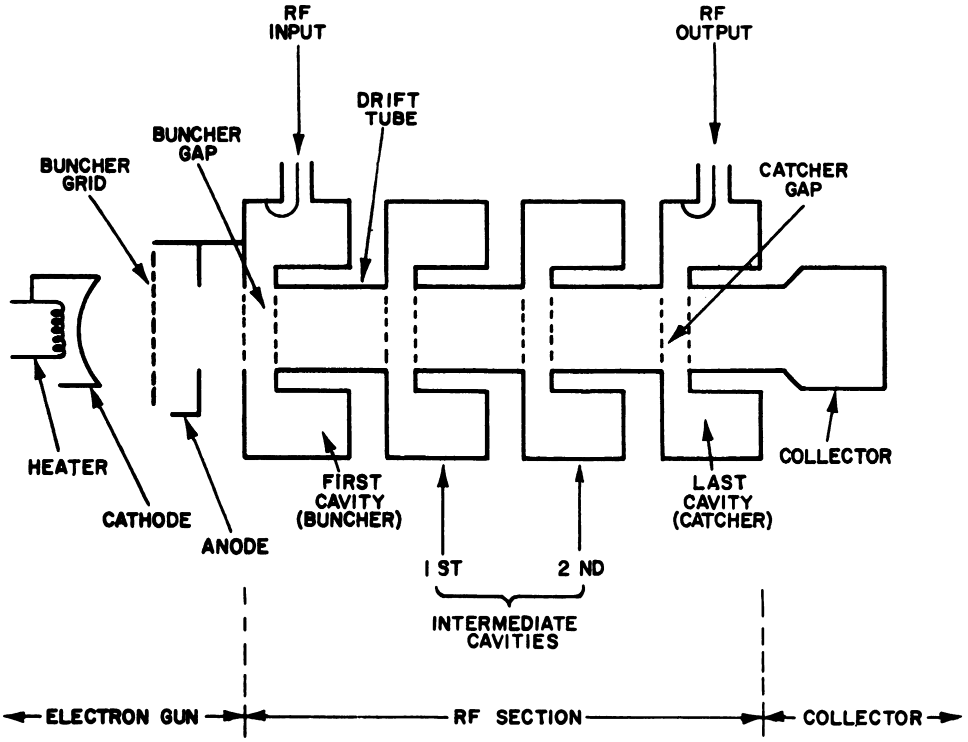

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Figure 4-48.—Multicavity power klystron amplifier.

must also be larger to allow for greater heat dissipation. In a high-power klystron, the electron beam may strike the collector with sufficient energy to cause the emission of X-rays from the collector. Many klystrons have a lead shield around the collector as protection against X-rays. Most high-power klystrons are liquid cooled and must be constructed to facilitate cooling the collector.

Klystron amplifiers have been built (to the present time) with as many as seven cavities (that is, with five intermediate cavities). The effect of the intermediate cavities is to improve the bunching process. This results in increased efficiency. Adding more intermediate cavities is roughly analogous to adding more stages to an IF amplifier. That is, the overall amplifier gain is increased and the overall bandwidth is reduced, if all the stages are tuned to the same frequency. The same effect occurs with klystron amplifier tuning. A given klystron amplifier tube will deliver high gain and narrow bandwidth if all the cavities are tuned to the same frequency. This is called *synchronous tuning*. If the cavities are tuned to slightly different frequencies, the gain of the klystron amplifier will be reduced and the bandwidth may be appreciably increased. This is called *stagger* or *asynchronous tuning*. Most klystron amplifiers that feature relatively wide bandwidths are stagger tuned.

The klystron is not a perfectly linear amplifier; that is, the rf power output is not linearly related to the rf power input at all operating levels. Another way of stating this is that the klystron amplifier will saturate, just as a triode amplifier will limit if the input signal becomes too large. In fact, if the rf input is increased to levels above saturation, the rf power output will actually decrease. Figure 4-49 shows a plot of typical klystron amplifier performance for various tuning conditions. The rf output is plotted as a function of the rf input. Curve A of figure 4-49 shows typical performance for synchronous tuning. Under these conditions, the tube has maximum gain. The power output is almost perfectly linear with respect to the power input, up to about 70% of saturation. However, as the rf input is increased beyond that point, the gain decreases and the tube saturates. As the rf input is increased beyond saturation, the rf output decreases.

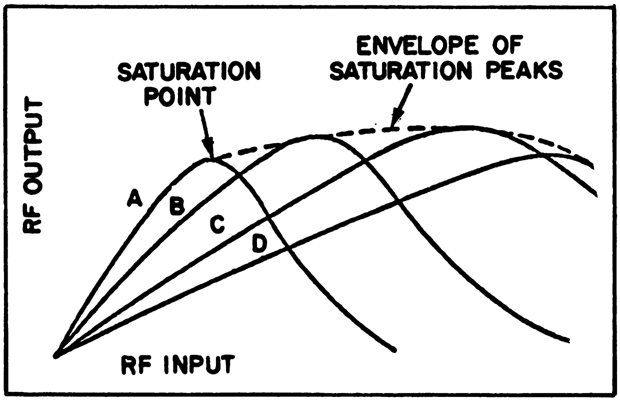

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**Figure 4-49.—Plot of typical klystron amplifier performance for various tuning conditions.**

To better understand the reason for this decrease, recall that in the previous discussion electron bunches were formed by the action of the rf voltage across the input cavity gap. This rf voltage accelerated some electrons and slowed down other electrons, resulting in formation of bunches in the drift tube region. Obviously, this speeding up and slowing down effect will be increased as the rf drive power is increased. The saturation point, shown on figure 4-49, is reached when the bunches are most perfectly formed at the instant they reach the output cavity gap. This results in the maximum power output condition. When the rf input is increased beyond this point, the bunches are perfectly formed before they reach the output gap; that is, they form too soon. By the time the bunches have reached the output gap, they tend to debunch because of the mutual repulsion of electrons and because the faster electrons have overtaken and passed slower electrons. This causes the power output to decrease.

If a multicavity klystron power amplifier is synchronously tuned and the next to last cavity is then tuned to a higher frequency, the gain of the amplifier is reduced, but the saturation power output level may be increased. This effect is shown by curves B and C of figure 4-49. Curve B represents a small amount of detuning of the next to last cavity, and curve C represents even more detuning. Note that the gain of the tube has been reduced and the saturation output power is higher than that obtained with synchronous tuning (curve A). Many klystron amplifiers are operated stagger tuned because of the resulting higher output power capability with the same beam power input. This increases the efficiency, provided, of course, that enough rf drive power is available to operate under the stagger-tuned condition. Also, as mentioned previously, stagger tuning results in a wider amplifier bandwidth.

As might be expected, stagger tuning may be carried too far, at which point the saturation output power drops. This is shown by curve D of figure 4-49.

**FOCUSING.**—One very important item that is required for high-power klystron amplifier operation is an axial magnetic field (that is, a magnetic field parallel to the axis of the klystron). In klystron amplifiers, which are physically long, it is difficult to keep the electron beam properly formed during its travel through the rf section. The mutual repulsion between electrons causes the beam to spread in a direction perpendicular to the axis of the tube. If this is allowed to occur, electrons will strike the drift tube and be collected there, rather than passing through the drift tube to the collector.

To overcome beam spreading, an axial magnetic field is used. The action of the magnetic field is to exert a force on the electrons that keeps them focused into a narrow beam. The magnetic field may be developed by a permanent magnet or by one or more electromagnets. A permanent magnet is used on tubes that are physically small or of medium power rating. Unfortunately, the size and weight of a permanent magnet are excessive for long or high-power tubes, making it necessary to use electromagnets. In some large tubes, several separate electromagnets are used. The current in each coil is individually adjustable to optimize the magnetic field shape. The magnetic field is normally terminated a short distance beyond the output cavity so that the beam may spread before it hits the collector. This tends to spread the electron beam interception over a large surface on the collector, minimizing collector cooling problems, which would result from the beam remaining concentrated at the time of interception.

Even with an axial magnetic field, some electrons stray from the main electron beam. These electrons are intercepted by the anode or klystron drift tubes. In high-power tubes, it is particularly important to minimize the number of stray electrons because of the heat generated when they strike the drift tubes. In a high-power klystron, this heating may be a very severe problem because drift tubes are very difficult to cool. Temperatures may become high enough to melt the drift tubes and thus destroy the tube.

The collector is normally insulated from the rf section of large klystron amplifiers to permit separate metering of the electrons intercepted by the drift tubes and those intercepted by the collector. The electrons intercepted by the rf section are normally called *body current*, while electrons intercepted by the collector are normally referred to as *collector current*. Obviously, the sum of body current and collector current is equal to the total current in the electron beam, which is called *beam current*. Klystron amplifier specifications often place a maximum limit on allowable body current.

In the previous discussion of klystron operation, it was implied that klystron amplifiers normally have actual metal grid structures across the gaps in the resonant cavities. Many low-power klystrons do indeed have wire mesh grids. However, most high-power klystrons do not have actual grids across the gaps. Such grids would intercept sizable quantities of electrons.

It is very difficult to cool grid structures, and a large amount of beam interception would melt the grids, thus destroying the tube. Fortunately, by proper design, the klystron may be made to operate efficiently without actual grid wires across the cavity gaps. The absence of these grids does not change the operating principles discussed previously, but it does have a secondary effect on klystron performance. If the electron beam has a small diameter compared to the diameter of the drift tube, the beam does not couple energy to the cavities very well. Therefore, the performance of a klystron amplifier, which does not have gridded gaps, may sometimes be improved by permitting the electron beam to be as wide as possible, while keeping the body current down to the maximum specified for the tube. The width of the beam may be somewhat controlled by the magnetic field strength.

Body current usually increases with rf input level because it is the rf input that causes the bunches to form. The dense electron concentration in the bunch causes mutual repulsion of electrons, and the diameter of the bunch may become larger than the diameter of the beam with no bunches present. Consequently, some of the electrons in the bunch may be lost to the drift tubes, and the body current may increase.

**ASSOCIATED EQUIPMENT.**—In the preceding sections, the basic theory of klystron operation has been discussed. Considerable additional equipment is required for a complete amplifier system. Various power supplies are necessary to deliver the required voltages and current. In high-power systems, a method of cooling is required. Various rf circuit components are required to control and measure the rf input to the klystron tube and to measure the rf output from the tube. A large collection of meters and protective devices are needed to monitor performance and protect operating personnel and equipment in the event of a malfunction or operator error. Figure 4-50 is a simplified diagram showing some of the power supplies, monitoring devices, and protective devices used in a typical power klystron amplifier.

In most klystron tubes, the anode and rf section are connected together inside the vacuum envelope. These parts are normally called the *tube body* and are generally operated at ground potential. It is convenient to operate the tube body at ground potential because the input and output connections (either waveguide or coaxial) are then also at ground potential. This makes it easier to connect the klystron into the rest of the system. In addition, the cavity tuners are at ground potential, eliminating any danger to personnel tuning the tube.

The beam supply, shown in figure 4-50, supplies the voltage required to accelerate the electrons and form the beam. It must also deliver the required beam current. The crowbar system quickly discharges the beam supply in the event of an internal klystron arc or other high-voltage fault condition.

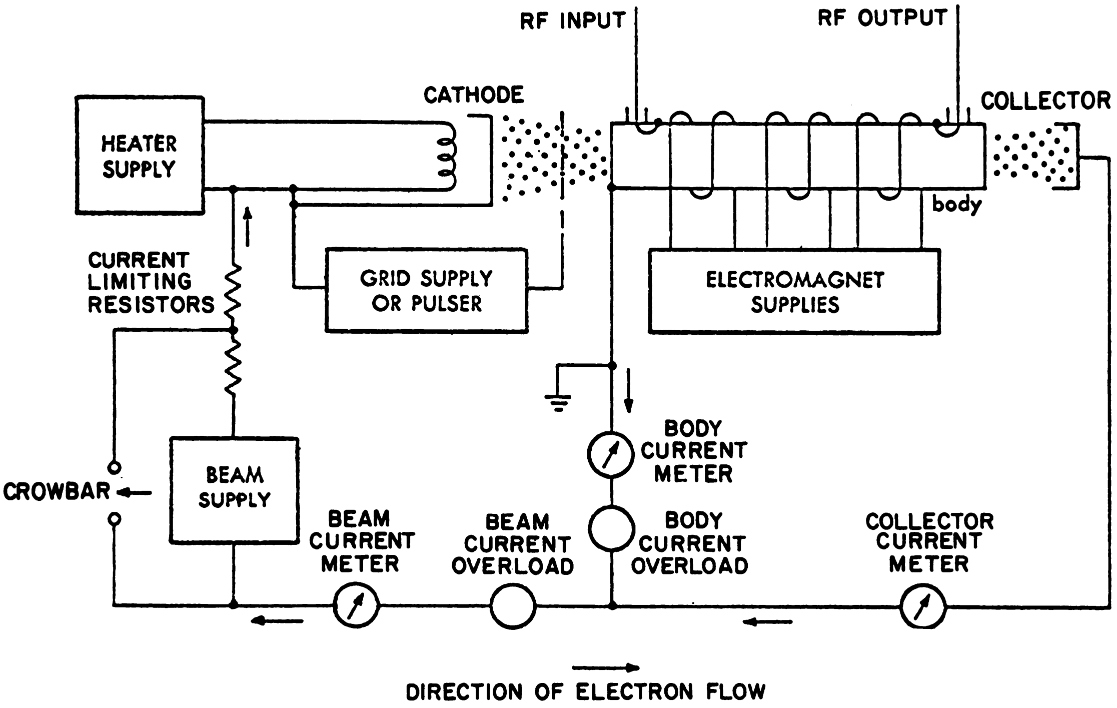

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Figure 4-50.—Associated klystron amplifier equipment.

For high-power systems, it is normal to have some value of series resistance between the beam supply and the klystron cathode. This limits tube current to a finite value if the tube should arc from cathode to ground.

Some klystrons have a grid or modulating anode that is used to control the number of electrons in the electron beam. Such grids are often used in pulsed systems to turn the tube full-on or full-off. A few systems employ grid modulation for the transmission of intelligence. In most gridded klystron tubes, the grid is never allowed to go positive with respect to the cathode. This might cause undue grid interception of the beam and result in burnout of the grid element. A grid power supply is required in those tubes that have grids. These power supplies and pulsers may take many forms, depending on the system application, and are not discussed here.

The collector of most high-power klystrons is insulated from the body of the tube. This allows separate metering and overload protection for the body current and collector current. In most systems, the collector and body operate at nearly the same potential. Normally, any potential difference is only the difference in voltage drop across the various metering circuits.

Figure 4-50 shows three electromagnets wrapped around the body of the klystron. Some klystrons are made with the electromagnets physically part of the tube itself. However, in most systems the electromagnets are separate from the tube, and the klystron is inserted into the electromagnet structure. Many modern klystrons have only one electromagnet, and, therefore, require only one power supply. Others may have as many as six separate coils, requiring one power supply for each coil. Voltage and current metering is usually supplied for each of the electromagnet power supplies. If an electromagnet power supply should fail, the electron beam would almost certainly spread, and most of the beam current would be intercepted on a small section of the drift tube. In most cases, this would cause the drift tube to melt and permanently destroy the tube. Therefore, klystron amplifier equipment normally has undercurrent protection in each of the electromagnet circuits. When the electromagnet current falls below a predetermined level, the beam supply is automatically turned off to prevent damage to the klystron. Redundant protection is provided by the body-current overload circuits, which also turn off the beam supply in the event of magnet current failure or misadjustment.

Also shown in figure 4-50 is a method used to monitor body current, collector current, and beam current separately. In many systems, separate monitoring of collector current is not done, since the collector current and total beam current are almost equal. It is quite unusual, in a relatively high-power klystron amplifier system, to allow the body current to exceed 10% of the beam current. High body current usually means low efficiency, and it increases the danger of burning out drift tubes. In very high-power klystrons, the body current is often limited to 1% to 2% of the total beam current. If a klystron arcs internally, the arc will always occur between cathode and anode. When this occurs, the body current immediately becomes excessive, tripping out the body-current overload relay. An arc also causes beam current to be much higher than normal, and the beam-current overload will also trip out. In fact, almost any high-voltage system fault (such as an insulation breakdown) will cause excessive current through the body-current meter and overload relay.

Because of the possibility of extremely high currents flowing under fault conditions, the protection of body-current and beam-current meters presents a somewhat difficult problem. This problem is usually solved by using very high-current, solid-state rectifiers, back to back, across the meters. In some cases, it is necessary to add a small resistance or inductance in series with the meter. Surge capacitors are normally placed across the combination. It is necessary to connect the rectifiers back to back because fault conditions often cause oscillating currents to flow through the meters.

**COOLING.**—Most low-power klystron amplifiers are air cooled, while all high-power klystrons are liquid cooled. At the present, state-of-the-art air cooling is usable up to about 1 kilowatt, cw. However, there are a few applications where liquid cooling is employed with tubes having an output as low as 10 watts.

The main source of power (and heat) in a klystron amplifier package is the beam power supply. The power generated by the beam supply must go somewhere. Part of it is converted to rf power, while the remainder eventually shows up as heat somewhere in the klystron. Klystron cooling is required to be able to dissipate the entire beam power. This is necessary because if no rf output is being generated (either due to low rf input power or detuning of the klystron tube), all of the beam power is dissipated as heat somewhere within the tube. As discussed previously, most of the electrons in the beam eventually strike the collector. When they strike the collector, their energy is dissipated as heat. The small fraction of the beam lost to the drift tube also generates heat.

Klystron amplifiers are normally between 30% to 50% efficient. Therefore, a tube rated at 10-kilowatt output must be designed to dissipate between 10 and 23 kilowatts respectively, depending on its efficiency. A tube rated at 100 kilowatts must be capable of dissipating between 100 and 230 kilowatts, depending on efficiency. As may be seen from the above discussion, very advanced cooling techniques are necessary. The power levels involved may melt a hole in the drift tube or collector in a small fraction of a second if the cooling system fails and adequate protective devices are not provided.

There are other smaller sources of heat in a klystron amplifier system. The heat produced by the heater is conducted and radiated to the exterior surfaces of the electron gun assembly and must be dissipated. Large tubes require a blower on the electron gun assembly to dissipate this heat. The power generated by the focus coil power supply is all dissipated in the electromagnet(s). Large electromagnets are usually liquid cooled. Should the electromagnet cooling fail, for any reason, the focus coil power supply must be shut off very quickly, or the magnet will burn out. The beam voltage must also be removed (preferably before turning off the focus coil supply) to protect the tube from excessive body current.

During operation, the walls of the resonant cavities have oscillating currents flowing in them. Although these cavities are made of very high conductivity metal, they still present a finite resistance to these oscillating currents. Therefore, heat is generated in the cavity walls. The amount of heat generated may be quite sizable in high-power, high-frequency tubes. For example, in a 20-kilowatt, cw, 10-GHz klystron amplifier, approximately 1 kilowatt of heat is generated by the circulating rf currents in the output cavity. Since the cavity is approximately a 1-inch cube, it is apparent that removing the heat is a formidable problem.

Another problem associated with cavity heating is not immediately apparent. The resonant frequency of a cavity depends on its physical size. The cavities are made of metal, which expands as its temperature increases. This effect tends to change the resonant frequency of the cavities and, thereby, detune the tube. As the tube detunes, the power output drops. This, in turn, results in a reduction of the rf heating, allowing the tube to come back into tune. If this problem was not considered in the initial tube design, the resulting tube would be unstable in its operation. This situation exists in some tubes that are external cavities. These external cavities are cooled by air rather than by liquid, and the cavity tuning is seriously affected by the ambient air temperature. All high-power klystrons are liquid cooled, including the cavities and tuners. The cavities are maintained at a stable temperature by controlling the temperature of the cooling liquid; therefore, thermal detuning is no longer a problem.

Drift tube heating is a serious problem in very high-power and medium-power, high-frequency klystrons. The drift tubes, which are inside the vacuum envelope, are physically small, and it is difficult to conduct the drift tube heat into the region outside the vacuum envelope. In some high-power tubes, it is necessary to bring the cooling liquid inside the vacuum envelope and around the drift tubes to remove the heat from them.

In some high-power, high-frequency systems, it is necessary to cool the output waveguide. A 10-GHz waveguide carrying a 5-kilowatt cw becomes too hot to touch in normal ambient air. Fortunately, waveguides may be cooled easily by soldering copper tubing along the sides of the guide and running cooling liquid through the tubing.

Systems that use blowers for cooling usually have an airflow switch. If the blower fails, the switch opens and removes power from appropriate power supplies. Systems employing liquid cooling normally distribute the liquid into a large number of paths, since the flow requirements are quite dissimilar. Each of the various paths have a low-flow interlock. If one of the liquid cooling circuits becomes plugged, the low-flow interlock opens and removes power from the system.

Some discussion of cooling liquids is appropriate here. Distilled water is the best medium for cooling klystron amplifiers. Some very high-power amplifiers specify that only distilled water may be used. Unfortunately, water freezes at a temperature that could be encountered under normal operating conditions. Many low- and medium-power klystrons permit the use of ethylene glycol and water as the cooling liquid. Ethylene glycol reacts with certain types of metals and hoses that might be used in the system. Therefore, special care must be taken in working on a system that uses ethylene glycol. Only nonferrous metals should be used in a cooling system for a klystron amplifier.

It should be stressed that the technician responsible for maintaining the klystron transmitter must be familiar with the cooling system of the equipment. Cooling systems are covered in chapter 6. Figure 4-51 shows a pictorial diagram of a high-power klystron amplifier and some of its associated components.

The above discussion should impress the reader with the fact that an expensive klystron amplifier system may be destroyed in a matter of seconds if the cooling system fails. A well-designed system uses many protective devices to prevent this from happening.

**NOISE IN KLYSTRON AMPLIFIERS.**— Volumes have been written about noise in microwave systems. Here, only the high points are covered.

The output of a klystron amplifier contains harmonics. This is primarily because the output cavity is excited by bunches of electrons that pass through the output gap once every cycle. Since the driving energy supplied to the output cavity is not continuous, but occurs in quick pulses, it is evident that the output current may not be purely sinusoidal. Therefore, the output contains harmonic components. In general, the harmonic output of a klystron amplifier is largest when the tube is operated at or above saturation. Harmonic content decreases when the tube is operated below saturation. Also, harmonics in the output may be reduced by the use of harmonic filters.

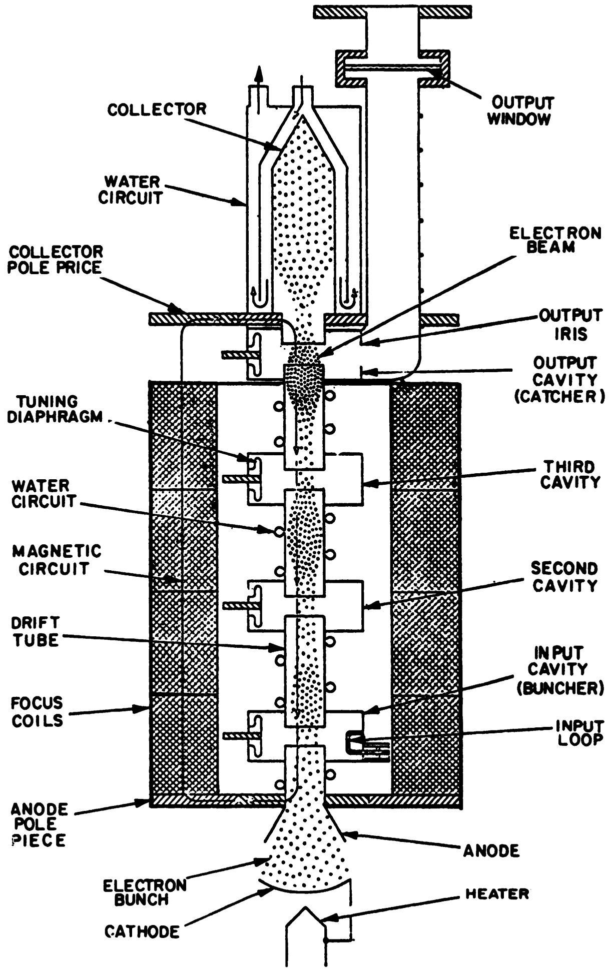

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**Figure 4-51.—Pictorial drawing of a high power klystron amplifier.**

Another source of distortion is the non-linearity of the klystron. If the rf signal is amplitude modulated, the rf output may not perfectly follow the rf input. This may result in distortion increasing as the tube is driven closer to saturation on the peaks of the rf input signal. In general, klystron amplifiers should not be used to amplify amplitude-modulated signals if the rf output is driven higher than 70% of the saturation level. Between 70% and 100% of saturation, considerable distortion may occur.

A klystron amplifier generates a certain amount of white noise, just as in any other electron tube. White noise occurs primarily because an electron beam is never perfectly homogeneous. The amount of electrons varies slightly with time, primarily due to shot noise at the cathode surface. This variation shows up as random noise in the rf output. A certain amount of noise may also be generated by electrons striking the drift tubes.

From the above discussion, it may be seen that a klystron amplifier is noisy. Therefore, power klystrons are not usually used to amplify weak microwave signals such as in a radar receiver rf amplifier.

### Traveling-Wave Tube (TWT)

The traveling-wave tube is a high-gain, low-noise, wide-bandwidth microwave amplifier. The TWTs are capable of gains of 40 db or more, with bandwidths of over an octave. (A bandwidth of 1 octave is one in which the upper frequency is twice the lower frequency.) The TWTs have been designed for frequencies as low as 300 MHz and as high as 50 GHz.

The primary use for the TWT is voltage amplification (although high-power TWTs, with characteristics similar to those of a power klystron, have been developed). Their wide bandwidth and low-noise characteristics make them ideal for use as rf amplifiers.

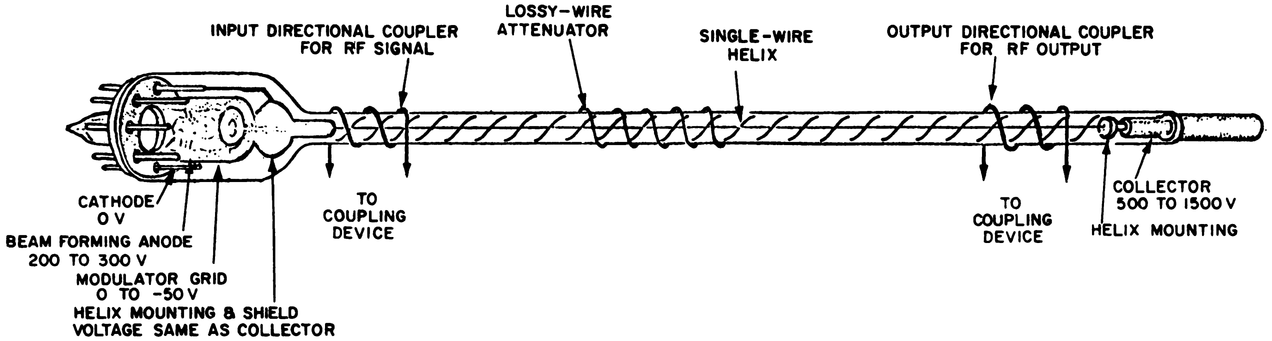
**CONSTRUCTION.**—Figure 4-52 is a pictorial diagram of a traveling-wave tube. The electron gun produces a stream of electrons that are focused into a narrow beam by an axial magnetic field, much the same as in a klystron tube. The field is produced by a permanent magnet or electromagnet (not shown) that surrounds the helix portion of the tube. The narrow beam is accelerated, as it passes through the helix, by a high potential on the helix and collector. The function of the helix is discussed later.

**OPERATION.**—Whereas the electron beam in a klystron travels, for the most part, in regions free from rf electric fields, the beam in a TWT is continually interacting with an rf electric field propagating along an external circuit surrounding the beam.

To obtain amplification, the TWT must propagate a wave whose phase velocity is nearly synchronous with the dc velocity of the electron beam. It is difficult to accelerate the beam to greater than about one-fifth the velocity of light. Therefore, the forward velocity of the rf field propagating along the helix must be reduced to nearly that of the beam.

The phase velocity in a waveguide, which is uniform in the direction of propagation, is always greater than the velocity of light. However, this velocity may be reduced below the velocity of light by introducing a periodic variation of the circuit in the direction of propagation. The simplest form of variation is obtained by wrapping the circuit in the form of a helix whose pitch is equal to the desired slowing factor.

As previously explained, the electron beam is focused and constrained to flow along the axis of the helix. The longitudinal components of the


LOSSY-WIRE ATTENUATOR
INPUT DIRECTIONAL COUPLER FOR RF SIGNAL
SINGLE-WIRE HELIX
OUTPUT DIRECTIONAL COUPLER FOR RF OUTPUT
CATHODE 0 V
BEAM FORMING ANODE 200 TO 300 V
MODULATOR GRID 0 TO -50 V
HELIX MOUNTING & SHIELD VOLTAGE SAME AS COLLECTOR
TO COUPLING DEVICE
TO COUPLING DEVICE
COLLECTOR 500 TO 1500 V
HELIX MOUNTING

179.728

Figure 4-52.—Pictorial diagram of a traveling wave tube.

input signal's rf electric field, along the axis of the helix or slow-wave structure, continually interact with the electron beam to provide the gain mechanism of TWTs. This interaction mechanism is pictured in figure 4-53. This figure shows the rf electric field of the input signal, propagating along the helix, infringing into the region occupied by the electron beam.

Consider first the case where the electron velocity is exactly synchronous with the circuit phase velocity. Here, the electrons experience a steady dc electric force that tends to bunch them around position A and debunch them around position B. This action is due to the accelerating and decelerating electric fields, and is similar to velocity and density modulation previously discussed. In this case, as many electrons are accelerated as are decelerated, hence, there is no net energy transfer between the beam and the rf electric field. To achieve amplification, the electron beam is adjusted to travel slightly faster than the rf electric field propagating along the helix. The bunching and debunching mechanisms just discussed are still at work, but the bunches now move slightly ahead of the fields on the helix. Under these conditions, more electrons are in the decelerating field to the right of A than are in the accelerating field to the right of B. Since more electrons are decelerated than are accelerated, the energy balance is no longer maintained. Thus, energy transfers from the beam to the rf field, and the field grows.

Fields may propagate in either direction along the helix. This leads to the possibility of oscillation due to reflections back along the helix. This tendency is minimized by placing resistive material near the input end of the slow-wave structure. This resistance may take the form of a lossy-wire attenuator (fig. 4-52) or a graphite coating placed on insulators adjacent to the helix. Such lossy sections completely absorb any backward traveling wave. The forward wave is also absorbed to a great extent, but the signal is carried past the attenuator by the bunches of electrons. These bunches are not affected by the attenuator, and, therefore, reinstitute the signal on the helix after they have passed the attenuator.

Some means must be provided to apply rf energy to one end of the helix and remove it from the other. Four methods of coupling are illustrated in figure 4-54.

Figure 4-54 illustrates *waveguide matching*. The waveguide is terminated in a nonreflecting impedance, and the helix is inserted into the waveguide, as shown. The system is efficient, but the waveguide has a far higher Q than the traveling-wave tube. This means that the broadband characteristics of the TWT suffer in that the entire bandwidth is not available for

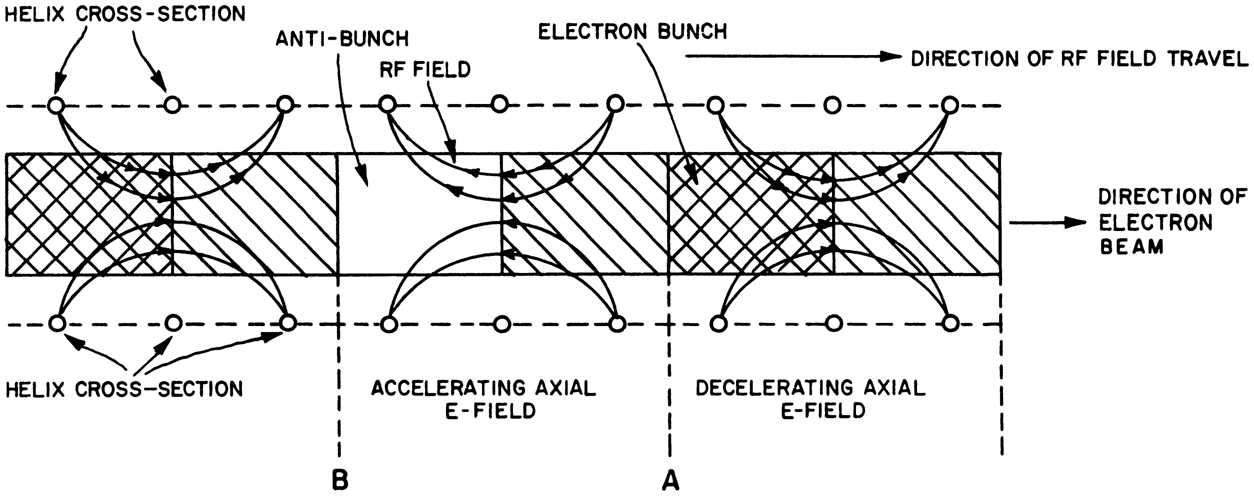

HELIX CROSS-SECTION
ANTI-BUNCH
RF FIELD
ELECTRON BUNCH
DIRECTION OF RF FIELD TRAVEL
DIRECTION OF ELECTRON BEAM
HELIX CROSS-SECTION
ACCELERATING AXIAL E-FIELD
DECELERATING AXIAL E-FIELD
B
A

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Figure 4-53.—Helix field interaction.

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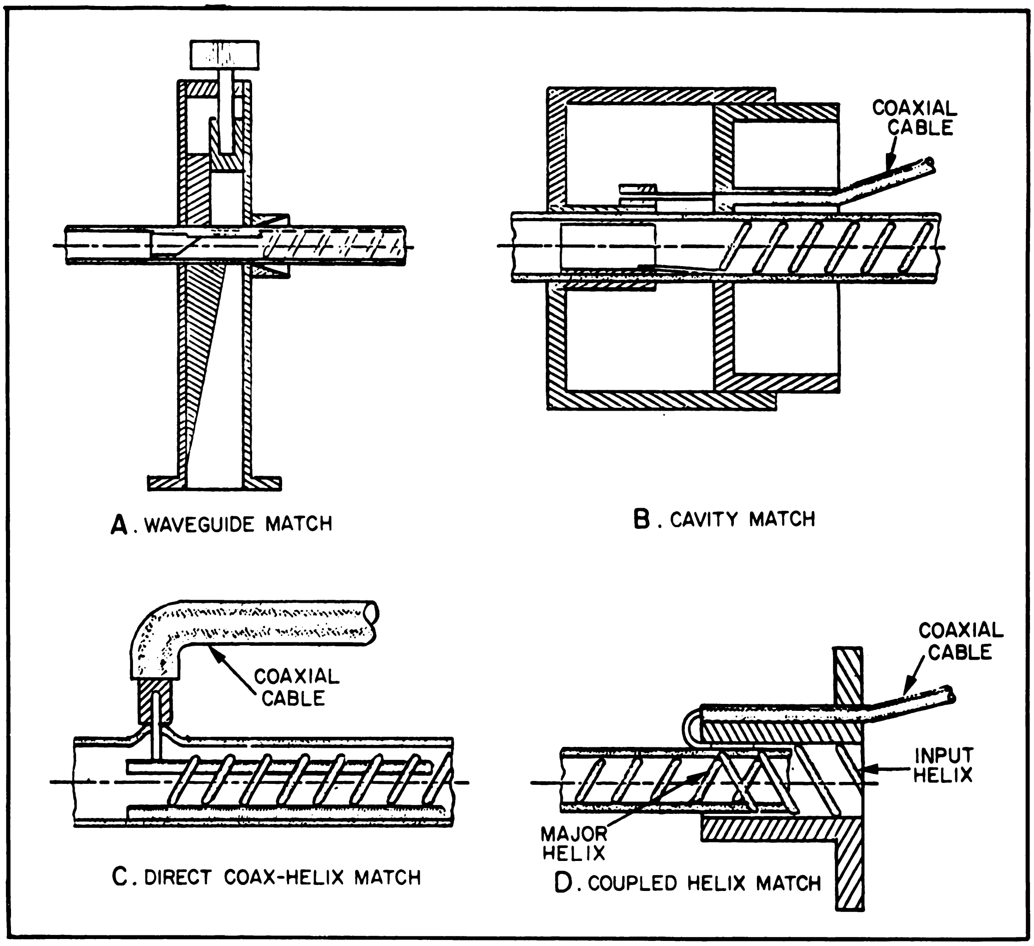

A. WAVEGUIDE MATCH B. CAVITY MATCH

C. DIRECT COAX-HELIX MATCH D. COUPLED HELIX MATCH

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**Figure 4-54.—TWT RF coupling.**

amplification. The waveguide can not respond over such a wide spectrum.

The *cavity match*, illustrated in figure 4-54, view B, is very similar to the waveguide match. Cavities may be made to resonate over wider ranges than waveguides, but they still have a high Q compared to the TWT. The helix is placed at the mouth of the cavity, thereby absorbing any E-field produced. The rf is fed into the cavity by a coaxial cable.

Figure 4-54, view C, illustrates a *direct coax-helix match*. It is the simplest system of all. The center conductor of the input coaxial cable is connected directly to the helix. Although this method is used quite frequently, it has a disadvantage. A high VSWR is set up by this match, and this causes heating around the input connection. Since this connection passes through the glass envelope, the envelope is subject to heating and breaking at this point. However, this is a major problem only in higher power TWTs.

Figure 4-54, view D, illustrates the *coupled helix match*. In this system, the coaxial center conductor is attached to a small helix. The major helix is inserted within this input helix where it acts as the secondary of a transformer. This system has a good VSWR and is broader in bandwidth than cavities or waveguides, although it is unable to handle large amounts of power. You should note that any of the above coupling methods may be used for input as well as output coupling.

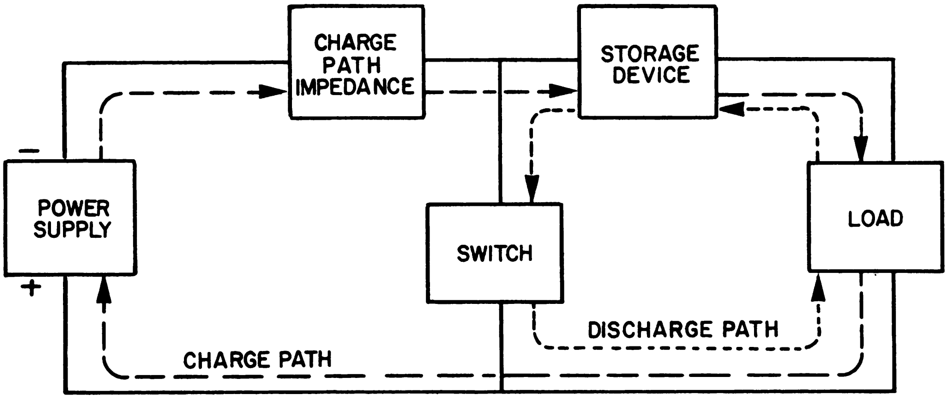

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Figure 4-55.—Basic elements of a modulator.

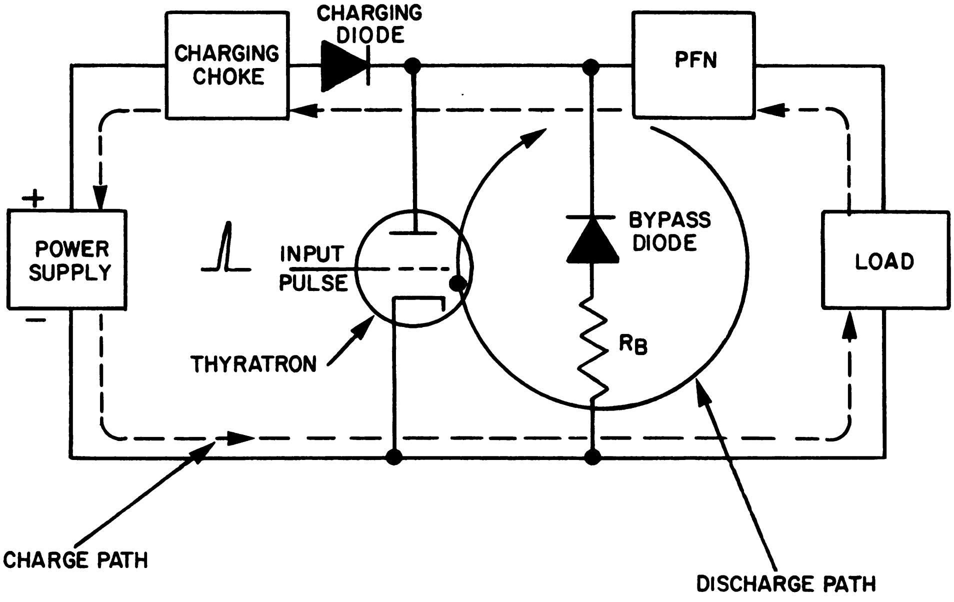

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Figure 4-56.—Modulator using a thyratron switch.

**TWT MIXER.**—The traveling-wave tube has also found application as a microwave mixer. By virtue of its wide bandwidth, the TWT can accommodate the frequencies generated by the heterodyning process (provided, of course, that the frequencies have been chosen to be within the range of the tube). The desired frequency is selected by the use of a filter on the output of the helix. A TWT mixer has the added advantage of providing gain as well as simply acting as a mixer.

**TWT MODULATION.**—A TWT may be modulated by applying the modulating signal to a modulator grid. The modulator grid may be used to turn the electron beam on and off, as in pulsed microwave applications, or to control the density of the beam and its ability to transfer energy to the traveling wave. Thus, the grid may be used to amplitude modulate the output.

**TWT OSCILLATOR.**—A forward-wave traveling-wave tube may be constructed to serve as a microwave oscillator. Physically, a TWT amplifier and oscillator differ in two major ways. The helix of the oscillator is longer than that of the amplifier, and there is no input connection to the oscillator. TWT oscillators are often called backward-wave oscillators (BWO) or carcinotrons.

The operating frequency of a TWT oscillator is determined by the pitch of the tube's helix. The oscillator may be tuned, within limits, by adjusting the operating potentials of the tube.

The electron beam, passing through the helix, induces an electromagnetic field in the helix. Although initially weak, this field will, through the action previously described, cause bunching of succeeding portions of the electron beam. With the proper potentials applied, the bunches of electrons reinforce the signal on the helix. This, in turn, increases the bunching of succeeding portions of the electron beam. The signal on the helix is sustained and amplified by this positive feedback, resulting from the exchange of energy between electron beam and helix.

## MODULATORS

The previously discussed, transmitter tubes all have one common requirement, a source of high voltage, whether they are operated in a cw or pulsed mode. A fixed high-voltage supply for cw operation is relatively simple compared to a pulsed high-voltage supply. A pulsed high-voltage power supply is called a modulator. The term *modulate* means to shape as well as to control. Modulators are also called pulsers or keyers, depending on their circuit function.

There are many different pulse modulators in use today. The most common type found in fire control applications is the *line-type modulator*. The basic elements of a line-type modulator are shown in figure 4-55. The power supply provides the source of high voltage to charge the storage device. The storage device can be capacitive, inductive, or a combination of capacitance and inductance that stores electrical energy in the form of an electrostatic or electromagnetic field. Electrostatic storage is the most common method used. The storage device is charged through the relatively high impedance of the charge path while the switch is open. The load is the high-power tube, which is usually connected by means of a step-up pulse transformer. The pulse transformer allows the dc to charge the storage device. When the switch is closed, a low-impedance discharge path is provided for the storage device through the pulse transformer. The charge time is long compared to the discharge time because of the differences in impedances. The switch is normally an electronic element such as a thyratron or a silicon controlled rectifier (SCR), since mechanical switching is impractical at the pulse-repetition frequencies used in most radars.

A more practical circuit is shown in figure 4-56 and the resulting voltage waveforms in figure 4-57. This line-type modulator uses a hydrogen thyratron as the switch and a pulse-forming network (PFN) as the storage device. The charging choke and charging diode are added so that the PFN can be charged to almost twice the value of the power supply. The bypass diode and resistor ($R_B$) prevent reverse charging of the PFN. When power is applied, the PFN will begin to take on a charge. The flow of the charging current causes a strong magnetic field to build up in the charging choke. As the charge on the PFN approaches the power supply potential, current will begin to decrease. The decrease in current flow will cause the magnetic field built up in the charging choke to collapse. The collapsing field has about 90% of the power supply potential stored and now acts as an additional power supply

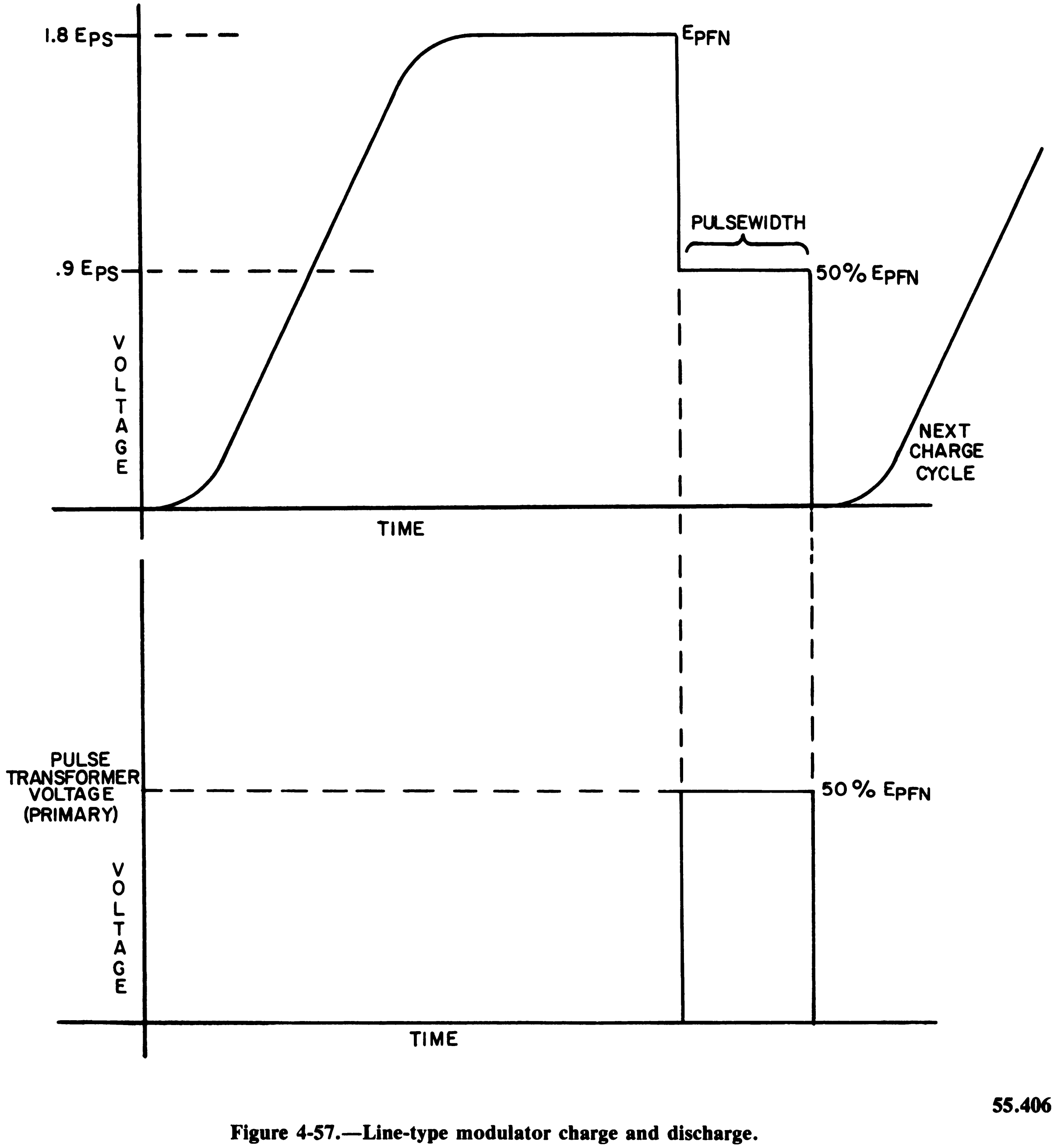

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Figure 4-57.—Line-type modulator charge and discharge.

in series with the source power supply. The collapsing field will charge the PFN to about 1.8 times the power supply potential. When the magnetic field has fully collapsed and current flow stops, the PFN will try to discharge down to the power supply level. Nevertheless, the charging diode acts as a hold-off diode preventing current flow in this direction. The PFN is now charged and ready to discharge when the thyratron is turned on. The thyratron is usually filled with hydrogen gas because it ionizes rapidly, presents a very low impedance, and is capable of handling very large current flows. The thyratron is ionized by an input pulse on the grid, generated in the radar timing and synchronization circuits. As the thyratron ionizes, it presents a very low-impedance path for the PFN to discharge through. The thyratron will remain ionized as long as the PFN is discharging. The time required for the PFN to discharge is determined by the inductance and capacitance of the PFN and the impedance of the discharge circuit. The PFN determines the pulsewidth of the high-voltage pulse applied to the load. The start of the high-voltage pulse only is determined by the pulse applied to the thyratron. If the impedance of the discharge circuit is equal to the impedance of the PFN, then the PFN will completely discharge into the load. However, slight mismatches are normally found and all of the energy in the PFN will not be discharged. This residual energy causes the PFN charge to swing to the opposite polarity. The bypass diode and resistor will now conduct on the reverse swings of the PFN charge and dissipate the residual energy. The bypass diode is also called an inverse or clipper diode in some circuit descriptions. If a bypass (inverse or clipper) diode is faulty, the PFN charge level for each cycle will vary with the amount of residual charge on the PFN. Fluctuations in charge levels cause corresponding high-voltage, pulse-amplitude fluctuations that cause rf power level changes and may even cause arcing in the high-power tube.

Some line-type modulators also include a damping circuit consisting of a diode and resistor in series tied across the primary (or secondary) of the pulse transformer, as shown in figure 4-58. The damper circuit presents a very high impedance compared to the primary of the pulse transformer. Therefore, the PFN discharge current will flow through the primary of the pulse transformer and not the damping circuit. At the end of the PFN discharge, oscillations in the pulse transformer, due to stray capacitance, leakage inductance, and mismatches, will cause the damping circuit to conduct and damp out the oscillations, as shown in figure 4-59.

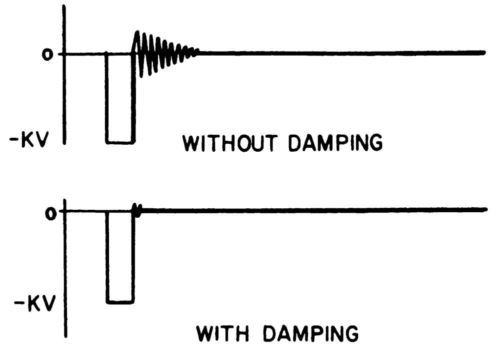

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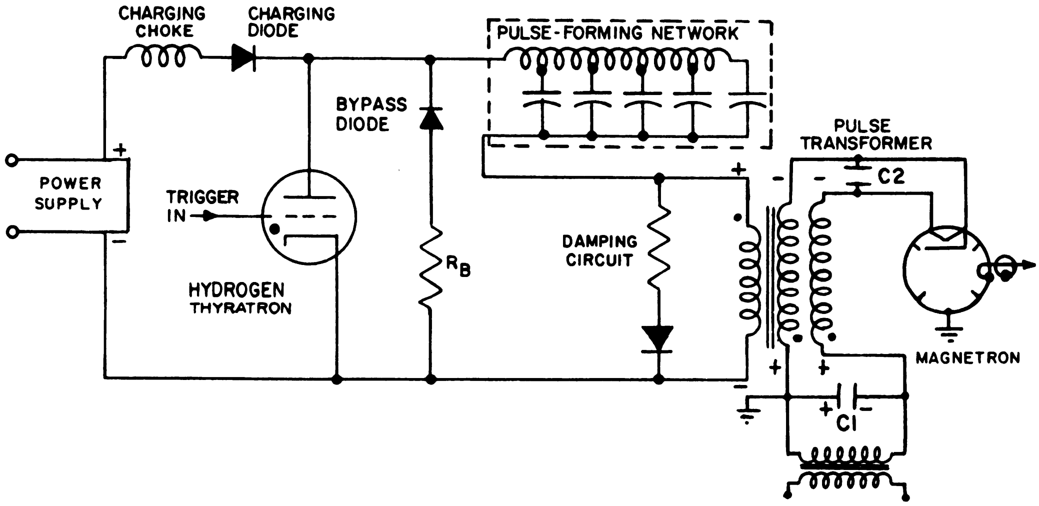
Figure 4-59.—Magnetron cathode pulse.



55.415

Figure 4-58.—Line-type modulator with damping circuit and bifilar wound pulse transformer.

The pulse transformer is a special step-up transformer that matches the impedance of the PFN to the high-power tube. Pulse transformer design is critical because of the high-frequency components present in the PFN output pulse. The core is composed of thin laminations of ferromagnetic material, usually silicon steel. Close coupling between primary and secondary reduces leakage inductance to preserve the steep, leading edge of the input pulse. Low interwinding capacitance is desired to prevent high-frequency oscillations. Close coupling is attained between primary and secondary by winding the primary directly on the secondary and by using the same leg of the core for both windings. The secondary is usually a bifilar winding.

The bifilar winding secondary is illustrated in figure 5-58. It is made up of two insulated conductors, wound side by side so that exactly the same voltage is induced in each. The bifilar winding acts as two secondaries that have equal and in-phase voltages induced in them. The bifilar winding permits the use of a filament secondary without high-voltage insulation.

Bypass capacitors, C1 and C2, are often used so that pulse current will flow directly to the bifilar winding, without affecting the filament circuit.

## RECEIVERS

The rf echo pulses reflected by a distant object are similar to the transmitted pulses, but they are considerably diminished in amplitude. These minute signals are amplified and converted into video pulses by the receiver. A voltage amplification in the order of $10^{10}$ is required to produce a video pulse of sufficient amplitude to intensify the beam of a CRT. The receiver must accomplish this amplification with minimum introduction of noise voltages.

In addition to having high-gain and a low-noise figure, the receiver must provide a sufficient bandwidth to pass the many harmonics contained in the video pulses. This is to minimize distortion of the pulses. The receiver must also accurately track, or follow, the transmitter in frequency, since drift diminishes the reception of the echo signal. The receiver tuning range need only be equal to that of the transmitter.

### RECEIVER SYSTEM FUNCTIONAL AREAS

The superheterodyne receiver is used exclusively in radar systems. A simple, block diagram of a radar receiver based on the superheterodyne principle is shown in figure 4-60. The echo signal enters the system by way of the antenna. It passes through the duplexer and is amplified by the low-noise rf amplifier (LNA). (TWTs, parametric amplifiers, and masers are representative devices that are used as low-noise, high-gain rf amplifiers.) When external noise is negligible, the noise generated by the input stage of the receiver largely determines the receiver sensitivity. In early radar receivers and many present day receivers, an LNA is not used, and the mixer is the first stage (as indicated by the dashed path in fig. 4-60). The function of the mixer stage, or first detector, is to translate the rf to a lower intermediate frequency, usually 30 or 60 MHz. This is accomplished by *heterodyning* the returning rf signal echo with a local oscillator signal in a nonlinear device (mixer) and extracting the signal component at the difference frequency (IF). By using the intermediate frequency, the necessary gain is easier to obtain than by using the higher rf. It is also easier to develop the response function (or bandpass characteristic) of the receiver IF stages.

One of the requirements of the radar receiver is that its internal noise be kept to a minimum. It is important, therefore, that the input stages of receivers be designed with low-noise figures. If the mixer is the first stage, its crystal characteristics will include low conversion loss and a low-noise to temperature-change ratio. Any noise generated by the local oscillator must be kept out of the mixer stage, either by the insertion of a narrow-band filter between the local oscillator and the crystal, or by the use of a balanced mixer.

As the bandwidth of the rf portion of the receiver is relatively wide, the frequency-response characteristic of the IF amplifier determines the overall response characteristic of the receiver. It is in the design of the IF portion of the receiver that the response characteristics are accomplished, as is also the signal-to-noise ratio.

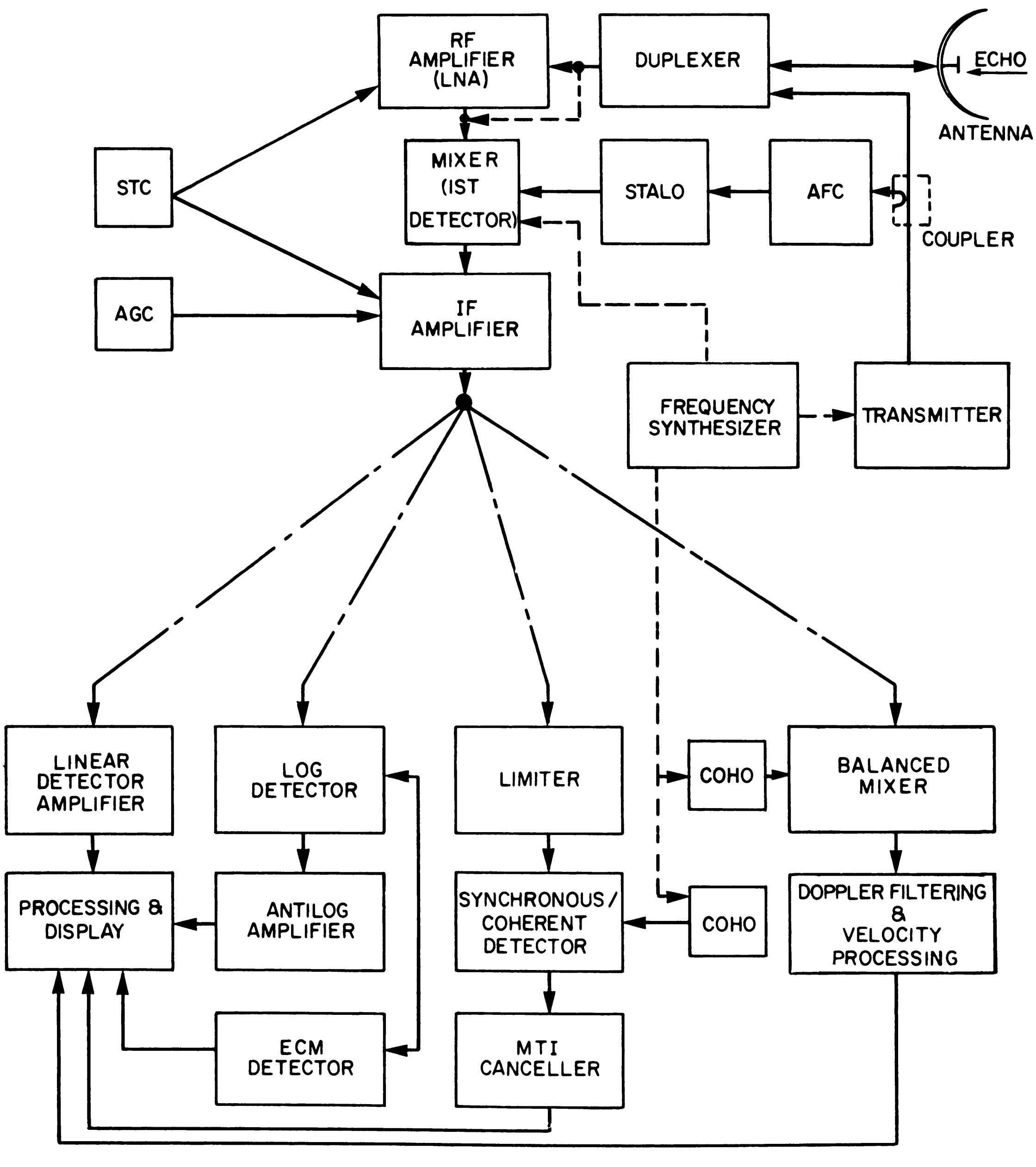


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Figure 4-60.—Radar receiver general functions.

### Automatic Frequency Control (AFC)

The AFC system (fig. 4-60) normally employed to keep the receiver in tune with the transmitter is known as a *difference-frequency system*. In this system, a portion of the transmitter signal is coupled into the AFC mixer and is heterodyned with the local oscillator signal. If the transmitter and receiver are correctly in tune, the resultant difference frequency will be at the correct IF. If the receiver is not in tune with the transmitter, the difference frequency will not be correct. Any deviation from the correct IF signal is detected by the AFC frequency discriminator, which, in turn, generates an error voltage. The error voltage magnitude is proportional to the deviation from the correct IF, and the polarity determines the direction of the error. The error voltage corrects the frequency of the local oscillator common to both the receiver mixer and AFC mixer.

Many of the newer radar systems eliminate the requirement for the AFC system by use of a special coherent frequency generator system. The base frequency is much lower than the transmitted frequency and is multiplied and mixed at different levels. The local oscillator signal is picked off at the appropriate level; therefore, it is locked to the transmitter frequency without an AFC system. This also allows frequency diversity and agility with each transmitted pulse, which an AFC circuit could not track.

## Local Oscillator

In radar, most receivers use 30- or 60-MHz intermediate frequencies. A highly important factor in receiver operation is the tracking stability of the local oscillator, which generates the frequency that beats with the incoming signal to produce the IF. For example, if the local oscillator frequency is 3,000 MHz, a frequency shift of as much as 0.1% would be a 3-MHz frequency shift. This is equal to the bandwidth of most receivers and would cause a considerable loss in gain. Bandwidth is the inverse of the pulsewidth, with a wider bandwidth for narrow pulses.

$$BW = \frac{1}{PW}$$

In receivers that use crystal mixers, the power required of the local oscillator is small, being only 20 to 50 milliwatts in the 4,000-MHz region. Because of the very loose coupling, only about 1 milliwatt actually reaches the crystal.

Another requirement of a local oscillator is that it must be tunable over a range of several megahertz. This is to compensate for changes in the transmitted frequencies and in its own frequency. It is desirable that the local oscillator have the capability of being tuned by varying the voltage applied to it.

Because the reflex klystron meets the above requirements, it is used as a local oscillator in some radar receivers. The schematic diagram of a reflex klystron is shown in figure 4-61.

Electrons accelerated by the accelerator grid are velocity modulated as they pass through the cavity grids (grids 2 and 3). The electrons, after passing through the cavity grids, move at different velocities. Since the repeller plate is made highly negative, the electrons progressing toward it stop and reverse their direction. The high-velocity electrons come physically closer to the repeller plate than either the medium- or low-velocity electrons. After repulsion, they are directed back toward the cavity grids. In the reflex klystron, ***bunching action*** occurs on the return trip of the electrons. In fact, bunching occurs immediately before the electrons come under the influence of the rf field about the cavity grids. The distance that the electrons move before they are repelled by the negative repeller plate is a function of the voltage values of the accelerating grid, the dc value of the voltage applied to the cavity grids, the dc voltage applied to the repeller plate, and the magnitude of the rf voltage coupled to the cavity grids by the cavity resonator. The voltages applied and the physical construction of the klystron should be of such values that the electrons will return to the cavity grids in bunches.

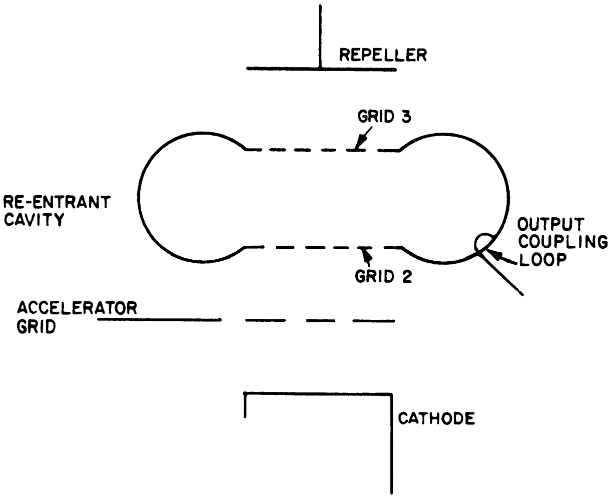

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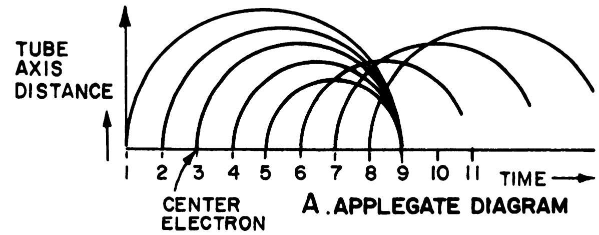
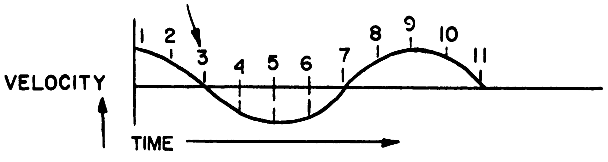
**Figure 4-61.—Reflex klystron schematic.**

To explain the bunching process, a diagram is shown in figure 4-62, view A. This diagram is sometimes referred to as an *Applegate diagram*. Figure 4-62, view B, shows a velocity-time diagram of the electrons during transit. The electron at time 3 (center electron) passes the cavity as the rf field (bunching voltage) is zero, and its velocity is unaffected. Therefore, an electron bunch will form about it. The electrons at times 1 and 2 pass the cavity with higher velocity, because they pass through the cavity at a time when the rf field (bunching voltage) across the cavity grids accelerates them. Therefore, they penetrate farther into the retarding field and return to the cavity at essentially the same time as the center electron (fig. 4-62, view A). Similarly, the electrons at times 4 and 5 leave with lower velocity, penetrate a shorter distance, and return at essentially the same instant as the three previous electrons.

The potential of the cavity grids when the repeller electrons return is important. The bunched electrons should be returned when the potential applied to the cavity grids is such that the energy of the returning bunches will be absorbed. The maximum absorption of energy occurs when the bunched electrons reach the midpoint between the cavity grids in coincidence with the maximum positive peak of rf voltage between these grids. As the electron bunch reaches the midpoint, the grid nearest the repeller plate must be positive in relation to the other buncher grid for correct alignment of the electrostatic field. The electron bunch will be decelerated in this field, thus expending some of its energy in sustaining rf oscillations within the grid cavity. For example, in figure 4-62, view B, the center electron (time 3) remains in the repelling field three-quarters of a cycle and the bunch (electrons at times 1, 2, 3, 4, and 5) return at time 9, when the cavity field has a maximum value in the direction to decelerate the returning bunch.



A .APPLEGATE DIAGRAM



B.VELOCITY-TIME DIAGRAM

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Figure 4-62.—Bunching process in reflex klystron.

Under these conditions, electrons leaving the cathode receive maximum acceleration from the cavity field, while returning electron bunches will receive maximum deceleration. If the grids are separated by approximately one-half a wavelength, the electron bunch would pass through the first grid (one nearest the repeller plate) as its rf potential is zero and changing from negative to positive. The electron bunch would pass through the second grid when its potential is zero, and it is changing from negative to positive. After the returning electron bunches have given their energy to the cavity, they are absorbed by the cavity grid nearest the cathode and are returned to the power supply.

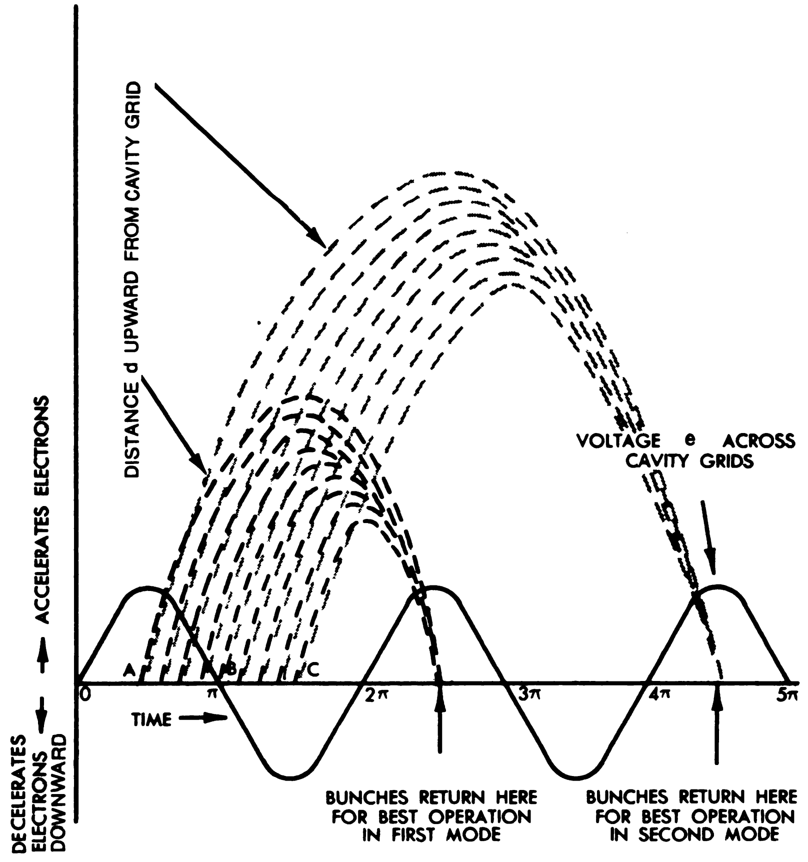
The cavity grids perform a dual function—velocity modulation and that of a catcher grid. The output from the tube is taken by use of the coupling loop shown in the diagram.

By proper adjustment of the negative voltage applied to the repeller plate, the electrons that have passed through the bunching field may be made to pass through the resonator again at the proper time to deliver energy to this circuit. Thus, the feedback needed to produce oscillations is obtained and the tube construction is greatly simplified. Spent electrons are removed from the tube by the positive accelerator grid or by the grids of the resonator. The operating frequency of the tube can be varied over a small range by changing the voltage on the repeller plate. This potential determines the transit time of the electrons between their first and second passages through the resonator. However, the output power of the oscillator is affected considerably more than the frequency by changes in the magnitude of the repeller voltage. This is because the output power depends upon the fact that the electrons are bunched at exactly the decelerating half-cycle of oscillating grid voltage. The volume of the resonant cavity is changed to change the oscillator frequency. The repeller voltage may be varied over a narrow range to provide minor adjustments in frequency.

It was mentioned that the electron bunches should arrive at the grids midpoint when the rf swing is at its maximum positive value on the grid closest to the repeller plate. It is not necessary for the electron bunches to return on the first positive half-cycle. They may be returned on the second, third, or fourth positive half-cycles. The positive half-cycle in which the electrons are returned and bunching occurs determines the mode of operations.

The mode of operation is determined by the transit time of the electrons. Transit time here means the time between when electrons leave the bunching grids and the time when the bunches deliver their energy to the cavity grids. Figure 4-63 shows the electrons being returned for the different operational modes. For the first mode, the bunching should occur three-quarters of a cycle after the average velocity electrons leave the bunching grids. The second mode of operation occurs one and three-quarter cycles after the average velocity electrons leave the bunching grids. The third mode of operation occurs after two and three-quarter cycles, and the fourth after three and three-quarter cycles. In practical operation, either the second, third, or fourth modes are used.

The mode of operation is determined by the transit time of the electrons. The transit time is a function of both the accelerator voltage and the repeller plate voltage. The mode of operation is controlled by the repeller plate voltage because the accelerating voltage is a fixed quantity.


DISTANCE d UPWARD FROM CAVITY GRID
VOLTAGE e ACROSS CAVITY GRIDS
ACCELERATES ELECTRONS
DECELERATES ELECTRONS DOWNWARD
A
B
C
0
π
2π
3π
4π
5π
TIME
BUNCHES RETURN HERE FOR BEST OPERATION IN FIRST MODE
BUNCHES RETURN HERE FOR BEST OPERATION IN SECOND MODE

25.193

Figure 4-63.—Modes of operation.

The variations of power output and frequency that occur as the repeller voltage of a reflex klystron is changed are particularly important characteristics of the tube. Figure 4-64 shows curves that may be obtained if the power output and frequency of a reflex klystron are measured as its repeller voltage is varied from zero to a large negative value, with the accelerating voltage and load remaining fixed. Oscillations occur only for certain ranges of the reflector voltage (corresponding to the voltage modes) for which the electron bunches return to the cavity in the proper phase to deliver energy to the cavity.

The center points of the modes (labeled A, B, and C, in fig. 4-64) correspond to reflector voltages for which the time spent by electrons in the retarding field is correct. That is, an integral number of cycles plus three-quarters of a cycle. At these points, the oscillation frequency is the resonant frequency of the cavity, and the power output is the maximum power of that mode. Note that the power outputs for the various modes at the resonant frequency are not the same and the output is least in the highest mode. This can be explained by examining the factors that limit the amplitude of oscillations, and which, in turn, limit the power output.

Power and amplitude limitations are due to overbunching as well as the usual losses in the oscillatory circuit. Overbunching occurs as oscillations build up and the bunching voltage becomes greater, thus increasing the amount of acceleration and deceleration. This causes bunching to occur in a shorter period of time (before the electrons reach the grids on the return trip), which tends to reduce the magnitude of oscillations. In the higher modes of oscillations where the bunches are formed more slowly, the electrons are more susceptible to overbunching.

As shown in figure 4-64, the frequency of oscillations in a reflex velocity-modulated tube is variable to a limited degree in any of the modes of operation by varying the repeller voltage. When the repeller voltage is varied, it causes a bunch to return either a little sooner or a little later than normal. Off resonance, the amplitude of oscillations decreases by an amount depending on the Q of the cavity. In this tube, the tuning range is small in comparison with the frequency of oscillations and varies somewhat from one mode to another. It is greatest in the highest mode because bunching and debunching take place at a slower rate. A greater variation from the ideal time of return is possible without debunching, which would cause the amplitude of oscillations to drop below the usable output level.

Another way to look at this is to consider that in the highest mode, the time required by an

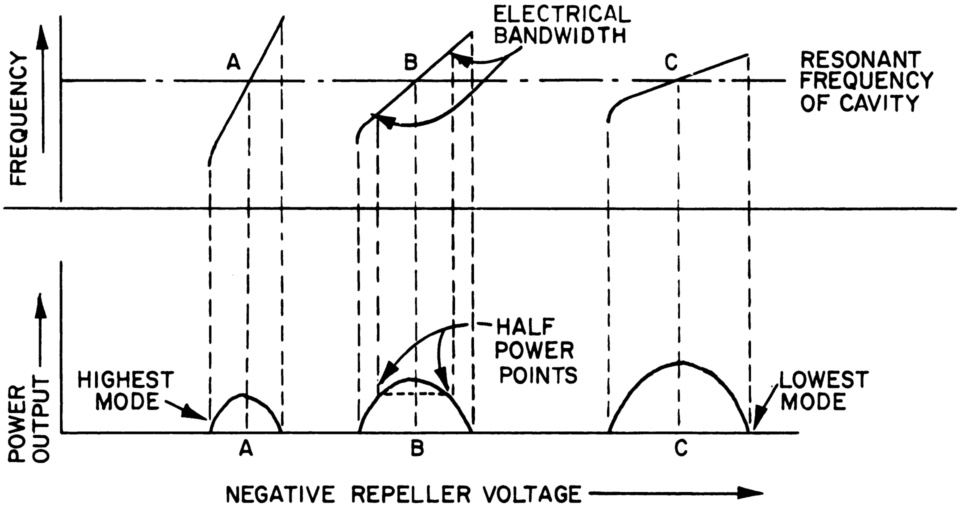


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Figure 4-64.—Power and frequency characteristics of reflex klystron.

electron leaving the grids to return is greater, and the change in period and its accompanying change in frequency occur in a shorter period. To illustrate, in the third mode the interval before return must be about two and three-quarter cycles. Therefore, a small change in the period of the bunching voltage would be only three-elevenths as great a portion of the interval as it would be if operation were in the first mode, where the ideal time interval is three-quarters of a cycle.

The band of frequencies that can be obtained by varying the repeller voltage lies between the half-power points, shown in figure 4-64. This range of frequencies is known as the *electrical bandwidth*. The power output curve of the bandwidth is unsymmetrical for the lower order voltage mode. This results from the fact that if the repeller voltage is increased, not only does the bunching voltage decrease and cause bunches to form at a later time, but the repeller voltage causes a quicker return. The effects of the two actions combine to cause poor bunching at the electrons return, resulting in a rapid drop in output on the high side of the hump. At lower voltages, however, even though the bunching voltage decreases and causes slower bunching, the decreased repeller voltage causes a later return to the grids. In this way, the two effects are counteracting and a greater change in repeller voltage is possible before the output drops below the usable level. The asymmetry is not noticeable in the higher order modes because the percentage change in bunching that can occur in a higher order mode is negligible.

As the local oscillator in a microwave receiver, a reflex klystron need not supply large amounts of power, but it should oscillate at a frequency that is relatively stable and easily controlled.

The need for a wide electronic tuning range suggests the use of a voltage mode of a high order. However, if a mode of excessively high order is selected, the power available is too small for local oscillator applications, and a compromise between wide range and power is necessary. Also, the use of a very high-order mode is undesirable because the noise output of a reflex klystron is essentially the same for all voltage modes. Thus, the closer coupling to the mixer required with high-order, low-power modes increases the receiver noise figure. Usually, the 1 3/4 or 2 3/4 voltage mode is found suitable. Since the modes are not symmetrical, the point of operation is usually a little below the resonant frequency of the cavity. This makes possible tuning above the operating frequency to a greater degree than if the precise resonant frequency was used.

In practice, the reflex klystron is used with an automatic frequency control circuit. Since, the repeller voltage is effective in making small changes in frequency, the AFC circuit is used to control the repeller voltage to maintain the correct intermediate frequency. It should be noted that the coarse frequency of oscillation is determined by the dimensions of the cavity, and there is, on most reflex klystrons, a coarse frequency adjustment, which varies the cavity size.

Reflex klystrons are also used as drivers for rf power amplifier klystrons. When used as drivers, the frequency and amplitude stability is much more critical. Any variation in driver frequency (frequency modulation) will be reproduced in the power amplifier output, and thus on the target echo signal. This FM variation can result in degraded Doppler tracking and velocity computations. If the FM deviation is large enough or the driver is not operated at the peak of a mode, then amplitude variations (amplitude modulation) will occur. The AM may be very small in magnitude on the driver signal, but after a gain of 30 dB or more in the power amplifier, the magnitude can be considerable. Both the FM and AM signals are undesirable and are classified as noise. Therefore, extra care in tuning and maintenance of the power supplies is required to minimize AM and FM noise generation.

### Frequency Synthesizers

Local oscillator configurations vary considerably, depending on the requirements of the individual radar system (alternate system shown by dotted lines in fig. 4-60). As discussed earlier, MTI, pulse-Doppler, and cw-Doppler radars require close control over the phase and frequency of the local oscillator to provide a means of coherent detection. Pulse-compression radar receivers also require close frequency and phase control for their form of coherent detection. A frequency synthesizer system (instead of STALO) is becoming more common in radar systems.

A basic coherent frequency synthesizer using phase-lock loops is shown in figure 4-65. The master oscillator is usually crystal controlled and limited to a frequency of about 10 MHz, and by the capabilities to cut thin crystals. The master oscillator output ($f^1$) is fed to harmonic frequency multipliers, which actually amplify a harmonic of $f^1$ rather than multiply frequencies. By using bandpass filters, only the harmonic that is desired is amplified. The three outputs of the harmonic amplifiers are separate frequencies that, when multiplied in the phase-lock loops, will produce the transmitter frequency input, receiver local oscillator input (to the mixer), and a subcarrier frequency for down conversion in the three phase-lock loops. A basic phase-lock loop is shown in figure 4-66. Each phase-lock loop (PLL) is locked to the phase of the master oscillator and the range of frequencies that can be produced is primarily controlled by the frequency select voltage. The PLL is designed to lock-in to a new frequency in only a few

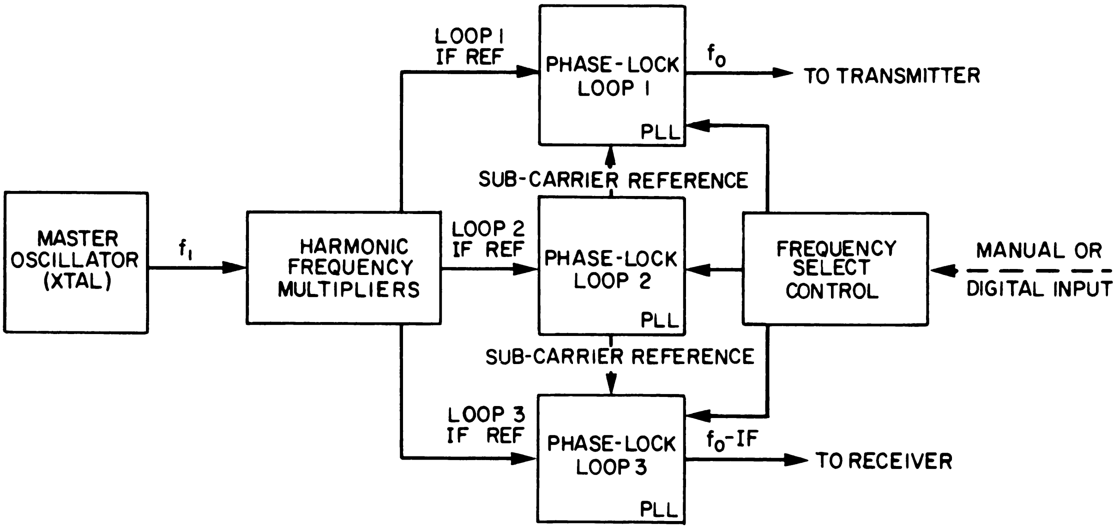

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Figure 4-65.—Frequency synthesizer.

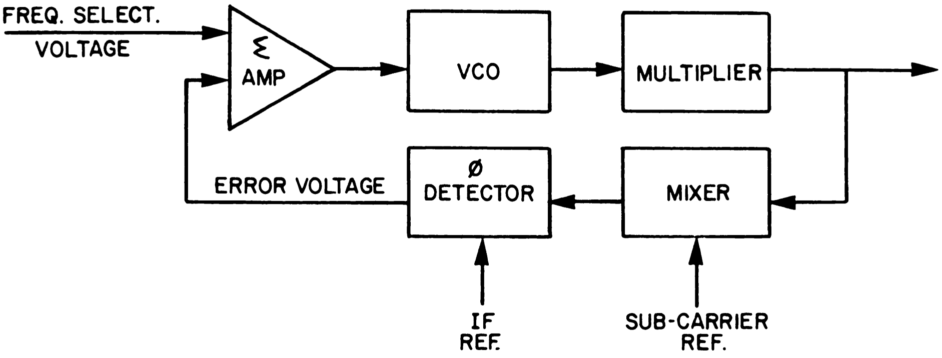

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Figure 4-66.—Phase-lock loop.

microseconds, therefore, allowing a different frequency for each transmitter cycle or pulse repetition interval.

A radar with frequency agility for each pulse repetition interval eliminates range ambiguities caused by target echoes returning after the next pulse interval begins.

Other frequency synthesizers use banks of crystals whose outputs are mixed in various combinations, then multiplied together to make up the different base frequencies and multiplied by harmonic amplifiers and phase-lock loops simular to those shown in figures 4-65 and 4-66. These are not the only possible configurations, but they are representative of how frequencies can be produced for radar transmitters and receivers.

## Radar Receiver Mixers

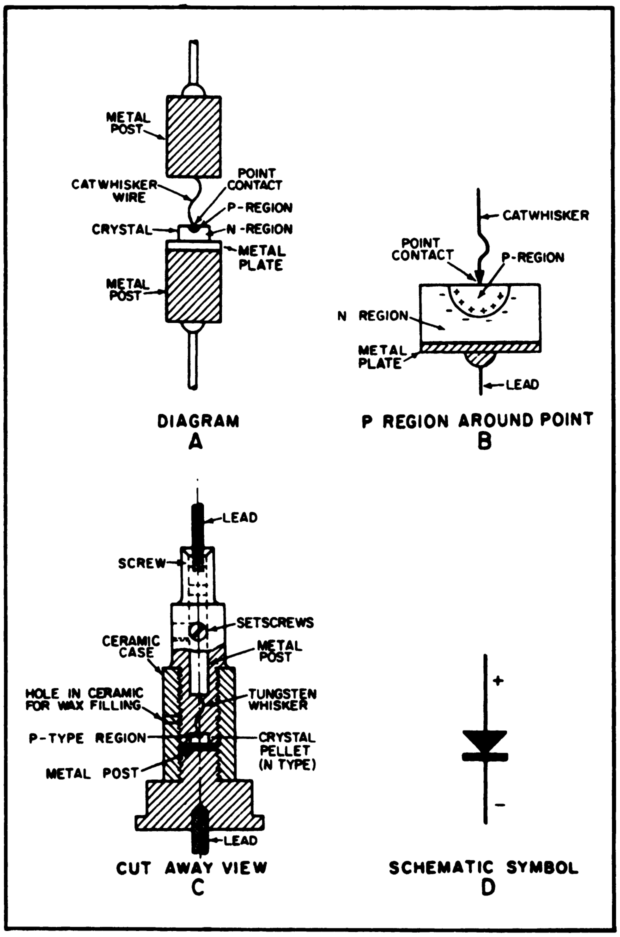
Many radar receivers do not use the rf amplifier stage, as indicated in figure 4-60. They use a crystal mixer stage as the receiver front end. If an rf amplifier is used, the design is critical because the weak signal levels could be easily masked by noise generated by components in the rf amplifier. Low-noise amplifiers (LNA) have solved some of the noise problems but are not in wide use in radar applications.

A type of crystal commonly used in mixers is the point contact silicon crystal diode. Unlike a junction diode, the point contact diode depends on the pressure of contact between a point and a semiconductor crystal for its operation. Figure 4-67, views A and B, shows a cutaway view of a point contact diode. One section of the diode consists of a small rectangular crystal of N-type silicon. A fine beryllium-copper, bronze-phosphor, or tungsten wire called the *catwhisker* presses against the crystal and forms the other part of the diode. During the manufacture of the point contact diode, a relatively large current is passed from the catwhisker to the silicon crystal. The result of this large current is the formation of a small region of P material around the crystal in the vicinity of the point contact, where a PN junction is formed.

The reason for using the pointed wire instead of a flat metal plate is to produce a high-intensity electric field at the point contact without using a large, external source voltage. It is not possible to apply large voltages across most semiconductors because of excessive heating.

The end of the catwhisker is one of the terminals of the diode. It has a low-resistance contact to the external circuit. A flat, metal plate on which the crystal is mounted forms the lower contact of the diode with the external circuit. Both contacts with the external circuit are low-resistance contacts.

The characteristics of the point contact diode under forward and reverse bias are somewhat



20.25

Figure 4-67.—Point contact diode.

different from those of the junction diode. With forward bias, the resistance of the point contact diode is higher than that of the junction diode. With reverse bias, the current flow through a point contact diode is not as independent of the voltage applied to the crystal as it is in the junction diode. The point contact diode has an advantage over the junction diode in that the capacitance between the catwhisker and the crystal is much less than the capacitance between the two sides of the junction diode. As such, the capacitive reactance existing across the point contact diode is higher, and the capacitive current that will flow in the circuit at high frequencies is smaller. A cutaway view of the entire point contact diode is shown in figure 4-67, view C. The schematic symbol of a point contact diode is shown in figure 4-67.

The simplest type of radar mixer is the single-ended or unbalanced crystal mixer. This type of mixer is shown in figure 4-68. The mixer shown uses a tuned section of coaxial transmission line that is one-half wavelength long and matches the crystal to the signal echo and the local oscillator (LO) inputs. Local oscillator injection is accomplished by means of a probe, while the signal is injected by means of a slot in the coaxial assembly. This slot would normally be inserted in the duplexer waveguide assembly (discussed in chapter 5) and properly oriented to provide coupling of the returned signal. In this application, the unwanted signals at the output of the mixer (the carrier, local oscillator, and the sum of these two signals) are effectively eliminated by a resonant circuit tuned to the intermediate, or difference, frequency. One advantage of the unbalanced crystal mixer is its simplicity. It has, however, one major disadvantage—its inability to cancel local oscillator noise. Recall that a klystron generates a high degree of noise, which makes it difficult to detect weak signals if that noise is allowed to pass through the mixer along with the signal.

One type of mixer that cancels local oscillator noise is the *balanced* or *hybrid mixer* (sometimes called the *magic T*). Figure 4-69 illustrates this type of mixer. In hybrid mixers, crystals are inserted directly into the waveguide. The crystals are located 1 quarter-wavelength from their respective short-circuited waveguide ends. This is a point of maximum voltage along a tuned line. The crystals are also connected to a balanced transformer, the secondary of which is tuned to the desire IF. The local oscillator signal is introduced into the waveguide local oscillator arm and distributes itself, as shown in

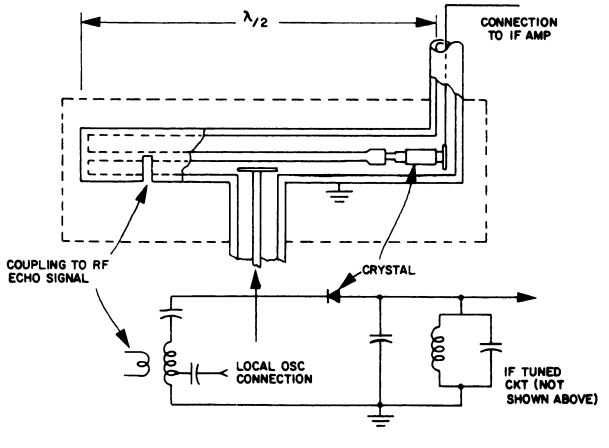


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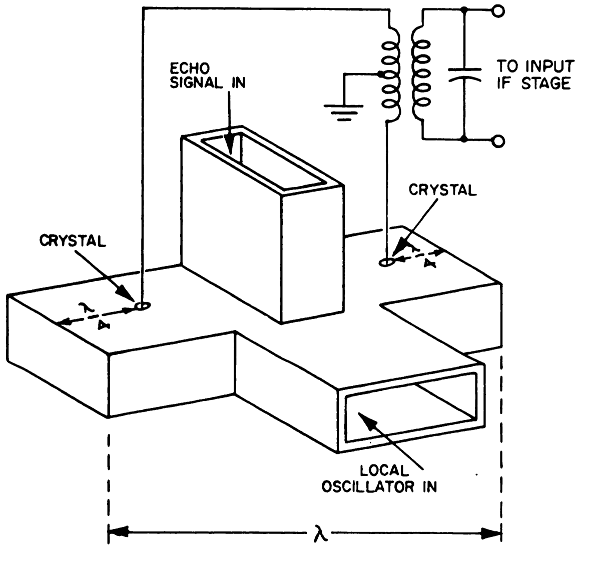
**Figure 4-68.—Single ended crystal mixer.**



67.31

**Figure 4-69.—Balanced hybrid crystal mixer.**

figure 4-70. Observe that the LO signal is in phase across the crystals. The echo signal is introduced into the echo signal arm of the waveguide and is out of phase across the crystals, as shown in figure 4-70, view B. The resulting fields are shown in figure 4-70, view C.

Since there is a difference in phase between echo signals applied across the two crystals, and because the signal applied to the crystals from the LO is in phase, there will be a condition when both signals applied to crystal number 1 will be in phase, and the signals applied to crystal number 2 will be out of phase. This means that an IF signal of one polarity will be produced across crystal number 1, and an IF signal of the opposite polarity will be produced across crystal number 2. When these two signals are applied to the balanced output transformer (fig. 4-69), they will add. Outputs of the same polarity will cancel across the balanced transformer.

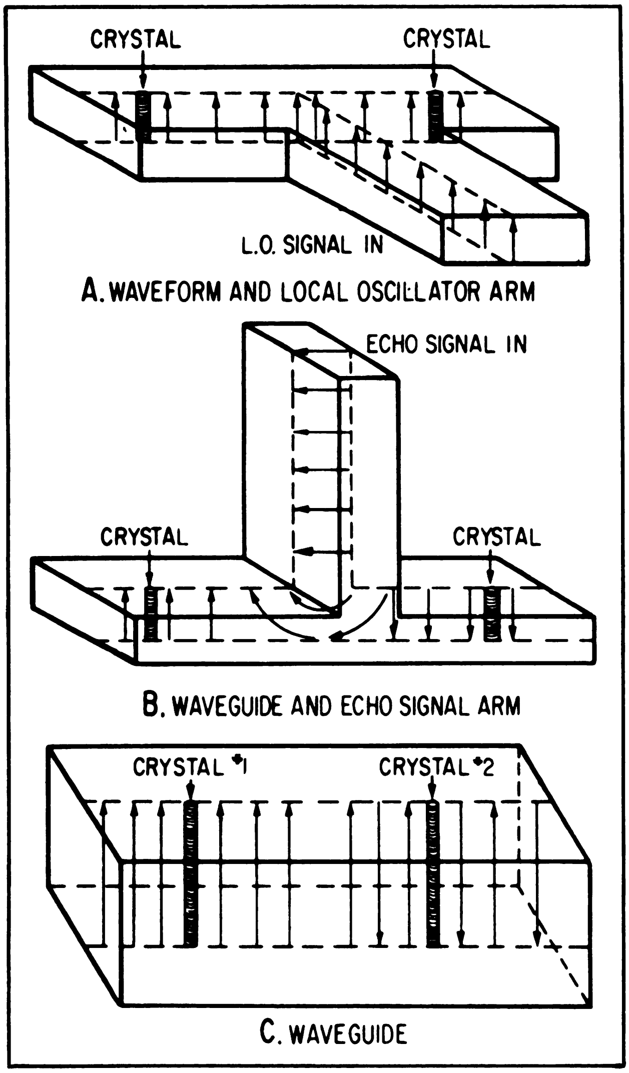


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Figure 4-70.—Balanced mixer fields.

It is this action that eliminates the LO noise. Noise components that are introduced from the LO are in phase across the crystals and are cancelled in the balanced transformer. It is necessary that the rf admittances of the crystals be nearly equal or the LO noise will not completely cancel. It should be noted that only the noise produced by the LO is canceled. Noise arriving with the echo signal is not affected.

## IF Amplifiers

The IF section of a radar receiver determines the receiver's gain, signal-to-noise ratio, and effective bandwidth. The IF amplifier stages must have sufficient gain and dynamic range to accommodate the expected variation of echo signal power. They must have a low-noise figure and a bandpass wide enough to accommodate the range of frequencies associated with the echo pulse.

The most critical stage of a radar receiver's IF section is the input or first stage. The excellence (figure of merit) of this stage depends on the noise figure of the receiver and the performance of the entire receiving system with respect to detection of small objects at long ranges. Not only must gain and bandwidth be considered in the design of the first IF stage, but also, and perhaps of more importance, noise generation in this stage must be low. Noise generated in the input IF stage will be amplified by succeeding stages and may exceed the echo signal in strength.

The IF stages succeeding the first stage usually achieve higher gain. This is possible because the signal level has been sufficiently increased by the low-noise input stage so as to preclude problems caused by noise generation. A commonly used IF circuit is the single-tuned amplifier. Each stage has only one tuning adjustment. Inductance is varied until resonance between it and the total shunt capacitance of the stage occurs at the desired IF.

As was previously stated, the IF stages require a wide bandwidth to accommodate the many frequencies that form the echo pulse. Insufficient bandwidth results in what is known as *transient distortion*. Transient distortion is the inability of the stages to amplify transients linearly. One type of transient distortion of a pulse is shown in figure 4-71. Transient distortion may result in ambiguities in the range of the target because of the nonlinear rise of the leading edge of the reproduced echo pulse.

The cascading of amplifier stages to achieve the high gain required in microwave IF amplifiers results in an overall bandwidth reduction. To compensate for this effect, the bandwidth of separate stages must be increased. This may be accomplished by several methods. One method is stagger tuning. The resonant frequencies of the various stages combine so that together they pass the frequency band to be amplified. The product of each stage's amplitude response curve forms the overall response curve. A response curve for stagger tuning is shown in figure 4-72.

Another method of increasing individual stage bandwidth is by using low Q tank circuits. This is possible since the stage bandwidth depends primarily on the tank circuit Q. A resistor called a *swamping resistor* is placed across the tank, and thereby reduces the circuit Q. The reduction in Q also results in a reduction in gain, and additional stages may be required to achieve the necessary amplification.

A third method of increasing bandwidth is double-tuned, stagger-tuned coupling. The response characteristic of such a double-tuned stage is dependent upon the degree of coupling. Amplitude response curves for varying degrees of

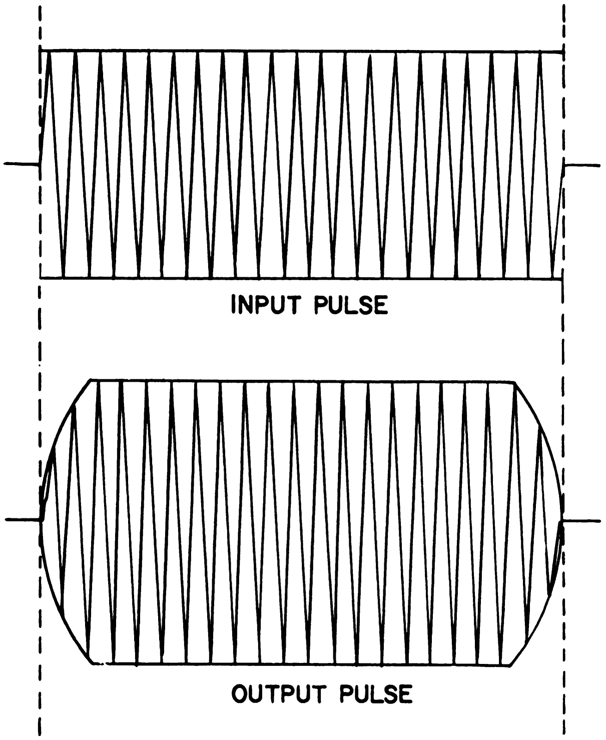

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Figure 4-71.—Transient distortion.

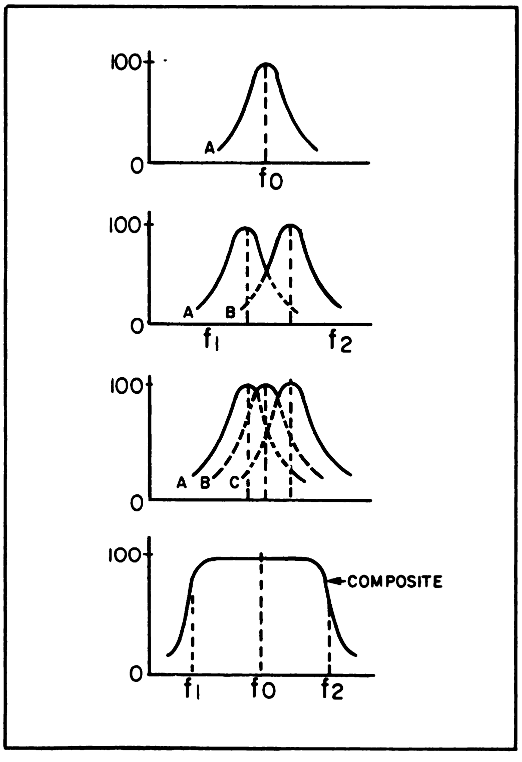

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Figure 4-72.—Stagger tuning response curve.

coupling are shown in figure 4-73. The degree of coupling usually employed is a form of overcoupling. Overcoupling occasionally produces oscillations in the vicinity of the pulse edges. Thus, if all stages of the IF amplifier section are double stagger tuned, coupling greater than transition (optimum) coupling should be avoided. An amplifier comprising only double stagger-tuned stages is difficult to adjust. Therefore, such stages are ordinarily used in combination with a greater number of single-tuned stages. In such an amplifier, the double-tuned stages may be over-coupled. The combination of double-tuned and single-tuned response curves yields a flat, overall characteristic response.

The gain of an IF amplifier is high. Because of this high gain, caution must be used to prevent the least amount of regenerative feedback. A small value of voltage in the proper phase fed back to a previous IF stage will cause the amplifier to break into oscillations. Therefore, great care is taken to minimize the possibility of positive feedback. Extensive decoupling in the circuits of microwave IF amplifiers is necessary and generally provided. The IF amplifiers in radar receivers are usually isolated and well shielded to prevent any undesired feedback or coupling.

### Gain Control

Automatic gain control (AGC) and sensitivity time control (STC) are common means of controlling the gain of IF amplifiers. STC may even be used in rf amplifier stages of some radar receivers. Radars detect targets of a wide variety of sizes, ranges, and reflective area. This produces a wide range of echo signal amplitudes that may exceed the dynamic range of a fixed gain receiver.

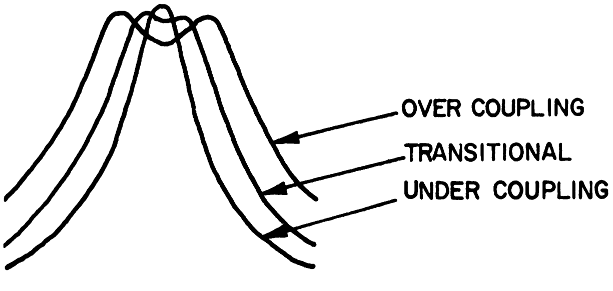

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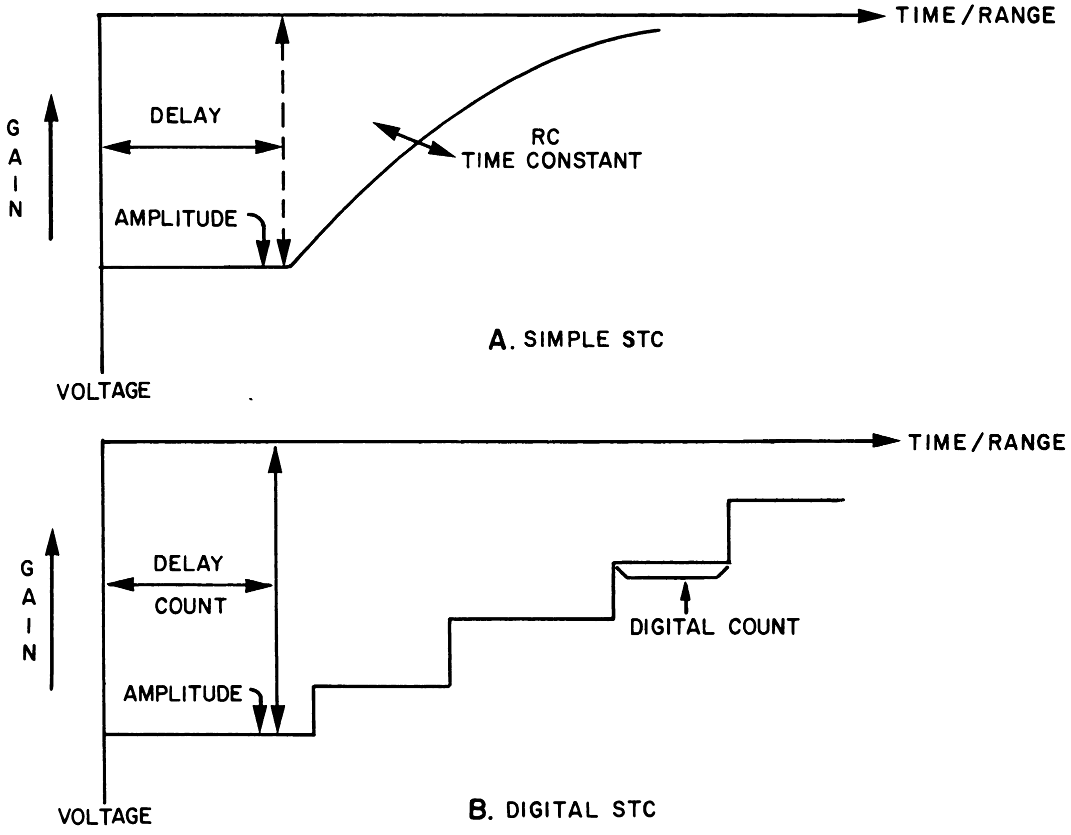
**Figure 4-73.—Double-tuned stagger-tuned response curves.**

**SENSITIVITY TIME CONTROL (STC).—** STC is used to control the gain of a radar receiver as a function of range. Close-in target echoes and clutter return is a greater amplitude than when they are at greater ranges. Using STC tends to equalize the amplitude of echoes independent of range. Several methods of STC are used, from the simple RC time constant to more elaborate digital schemes. Figure 4-74 shows several waveforms used to control gain with STC. The simple STC (fig. 4-74, view A) voltage depends on the RC time constant for discharge. The values of R and C are selected to provide a decay in five time constants to near zero within a maximum range. The start of the waveform may be adjusted to start at the end of the transmitted pulse or some other range value. The amplitude can also be adjusted to reduce receiver gain to a certain minimum value. The digital STC (fig. 4-74, view B) produces much the same effect, but uses stepped decreases to decrease the voltage and increase gain. The digital STC may be controlled by a computer to provide optimum gain as a function of range.

**AUTOMATIC GAIN CONTROL (AGC).—** Automatic gain control is common in most receiving systems, whether radar or communications. The AGC circuit detects the output from the IF amplifier and produces a voltage proportional to the strength of the detected signal and noise. For a close-in strong target return, a larger AGC voltage is produced and overall receiver gain is reduced; this produces the optimum signal strength out of the amplifier. This closes the AGC loop and produces a relatively constant amplitude signal out of the IF amplifier, independent of range.

### Logarithmic IF Amplifiers

When radars are operated where interference and clutter are encountered or jamming may occur, they can use techniques to adjust the receiver sensitivity as the interference varies in intensity. Digital processing uses a threshold criteria similar to that where an operator adjusts the sensitivity to the point where interference is



55.408

Figure 4-74.—STC waveforms.

just barely detectable. The process is called constant false-alarm rate (CFAR) when the radar receiver makes the adjustments automatically. Logarithmic amplifiers rely on the CFAR principle to amplify signals that exceed a certain threshold and provide only unity gain for those below the threshold. The threshold is automatically adjusted to maintain the same false-alarm rate.

A single stage of logarithmic IF amplifier is constructed just like the log summing loop discussed in chapter 2. The only difference is crossed diodes in the feedback path to allow for bipolar IF. The logarithmic amplifier is constantly adjusting the gain of the stage as a logarithmic function through the feedback diodes.

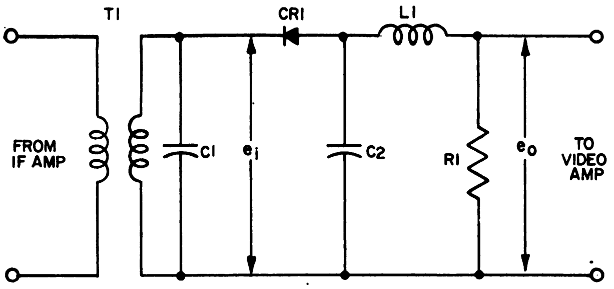
Logarithmic IF amplifiers are widely used in electronic countermeasure (ECM) receivers and monopulse angle tracking channels. Another recent use is in digital pulse compression and phase detection.

### Detectors

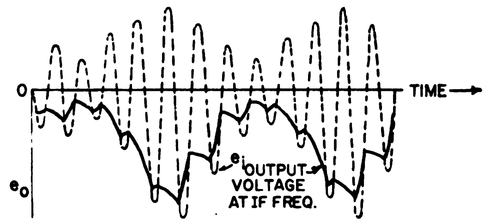
The detector in a basic radar receiver (fig. 4-60) converts the IF signal into a video signal to be displayed and/or processed for tracking. There are many forms of detection, and they vary depending on the type of radar and method of coherency used.

**LINEAR DETECTOR (DIODE DETECTOR).**—The simplest form of detector, and still commonly used, is the diode detector. It is classified as a linear detector because its output is directly proportional to the input.

A diode detector circuit is shown in figure 4-75, view A. The secondary of T1 and C1 form a tuned circuit that is resonant at the intermediate frequency. Should an echo pulse of sufficient amplitude be received, the voltage, $e_i$, developed across the tuned circuit is an IF pulse. The amplitude of this pulse is in the order of several volts. Its shape is indicated by the dashed line in figure 4-75, view B. Positive excursions of $e_i$ cause no current to flow through the diode. However, negative excursions result in a flow of diode current and a subsequent negative voltage, $e_o$, to be developed across R1 and C2. Between peak negative voltage excursions of the $e_i$ wave, capacitor C2 discharges through R1. Thus, the $e_o$ waveform is a negative video pulse with sloping edges and superimposed IF ripple, as indicated by the solid line in figure 4-75, view B. Negative polarity of the output pulse is ordinarily preferred, but a positive pulse may be obtained by reversing the connections of the diode. Inductance L1 (fig. 4-75, view A) in combination with wiring capacitance and C2 forms a low-pass filter. This filter attenuates the IF components in the $e_o$ waveform, but results in a minimum loss of video high-frequency components.



A. CIRCUIT



B. WAVEFORM

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Figure 4-75.—Typical diode detector.

**LOGARITHMIC DETECTOR.**—The logarithmic detector (fig. 4-60) has an output proportional to the logarithm of the IF envelope input. Logarithmic detectors are fairly common in electronic countermeasure (ECM) receivers. Logarithmic detectors usually have multiple stages where the overall gain varies logarithmically and are commonly called log detectors.

One form of log detector is combined with logarithmic IF amplifier stages, as shown in figure 4-76. Each stage has a low gain that is fixed above a set threshold. Any signal exceeding the threshold is amplified by only a factor of unity. All of the detector stages are summed together to provide a logarithmic output. The overall gain of a log detector-amplifier can be about 80 dB over the full range of the amplifier. The output, if used for display, is usually sent to an antilog amplifier first to normalize the video. Digital processing requires no antilog amplifier, since a threshold decision is made for each increment of echo signal.

### Phase-Sensitive Detector

In figure 4-60, a synchronous/coherent detector for MTI is shown. This type of detection has several possible configurations, based on the type of signal desired as an output. A phase (Ø) detector is one form of synchronous/coherent detector and has an output that has only phase information. A synchronous detector has both phase and amplitude information in its output. A balanced mixer has phase, amplitude, and frequency information in its output.

A phase-sensitive detector (Ø detector) is a key element in MTI radars. The Ø detector detects the phase-shift information caused by a moving target. The detector has inputs of the IF signal and the COHO signal, and it produces a video signal whose amplitude and polarity varies with phase differences only.

A Ø detector can be used in monopulse tracking radar receivers to determine the angular error of the target from the boresight center. Two identical receiver channels are required to provide azimuth and elevation error detection. The angle channel phase is compared to the range channel

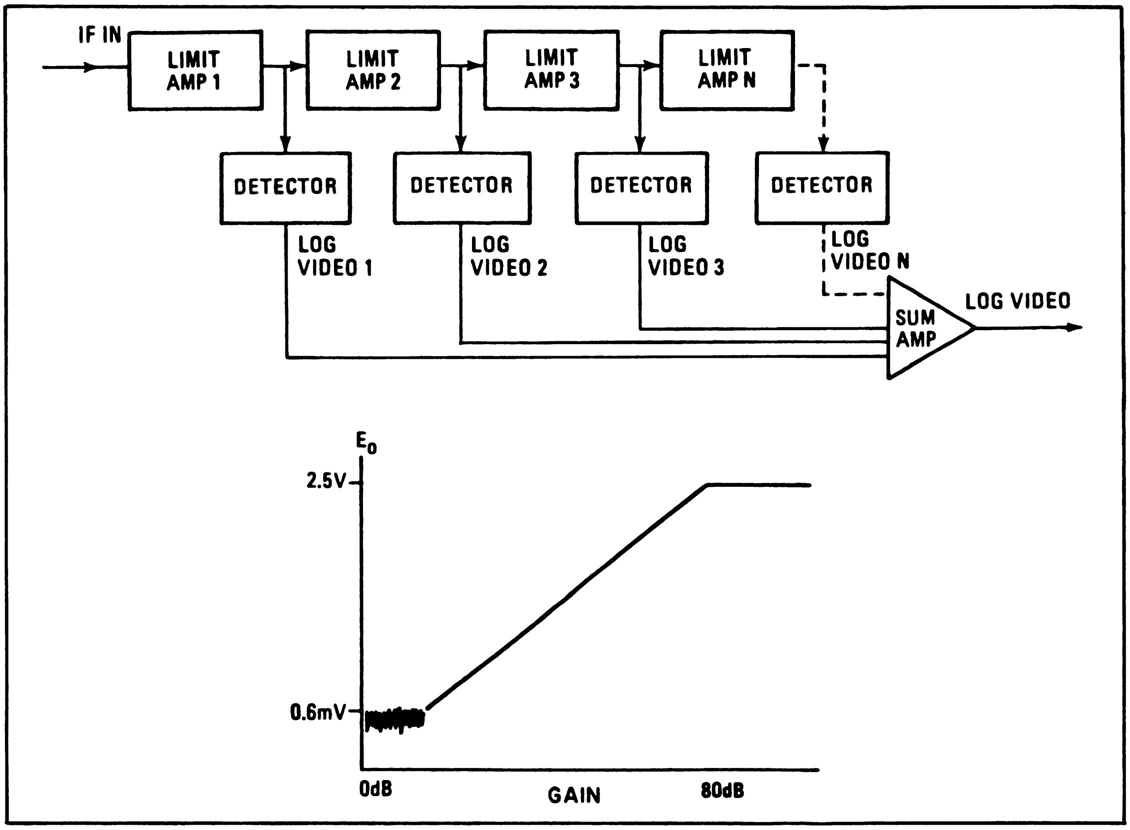

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Figure 4-76.—Logarithmic IF amplifier/detector, and output characteristics.

reference phase to produce a signal, whose amplitude and polarity indicate the amount and direction of phase error, which is directly related to the angle offset.

A synchronous detector can provide the same information as a phase detector in monopulse radars. The difference is that the phase comparison determines the polarity of the output signal only, while the amplitude comparison determines the amount of error.

A balanced mixer is more suited to use in cw and Doppler signal processing since frequency information is also contained in the output of balanced mixers. This signal is then fed to the filter bank for Doppler shift detection.

### Pulse Compression

Pulse compression was mentioned earlier in this chapter as a means of increasing the transmitted average power while retaining the range resolution of a narrow pulsewidth. Many fire control and search radars use pulse compression. Pulse compression radar has additional advantages over normal pulse radar; it has better discrimination of target echoes in clutter and is less susceptible to jamming. Two basic types of pulse compression can be found; they are linear FM and phase coding. Both encode the transmitted pulse with information that is compressed (decoded) in the receiver of the radar. Radars using pulse compression can compress pulses with durations of many microseconds down to a tenth of a microsecond. The ratio of transmitted pulsewidth to compressed pulsewidth is called the pulse compression ratio. Ratios of up to 160:1 are currently in use.

**LINEAR FM.**—Pulse compression using a swept FM during the transmitted pulsewidth is shown in figure 4-77. The wide transmitter pulsewidth (fig. 4-77, view A) can be just about any number of microseconds in duration. We will use 30 microseconds for an example. The carrier frequency is frequency modulated by linearly changing the frequency during the pulsewidth duration (fig. 4-77, view B). The transmitted signal and echo signals will then contain this information. The radar receiver will then remove the modulation from the IF signal by using a matched filter (pc filter). The PC filter is called a matched filter because it is matched to the modulation. The output of the PC filter (fig. 4-77, view C) will be delayed because of compression and will be near the end of the uncompressed pulse in time. This time delay is easily compensated for to yield accurate range measurements. The pulse compression ratio for figure 4-77 is 30:1.

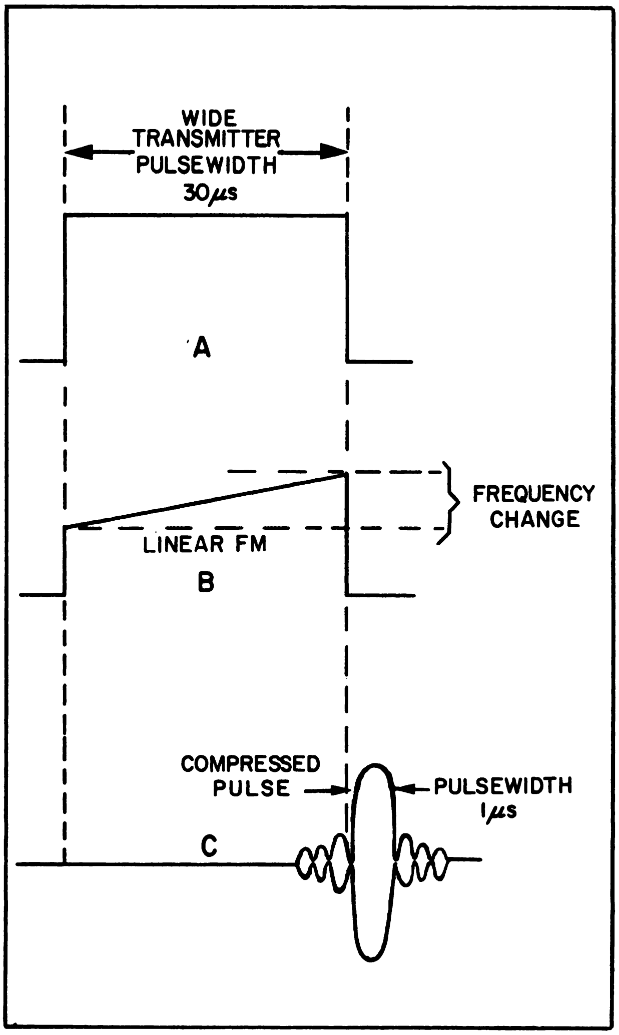

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Figure 4-77.—Linear FM pulse compression.

**PHASE-CODED PULSE COMPRESSION.**—Phase coding the transmitted pulse involves shifting the phase of the transmitter rf during the pulsewidth. A binary code is the normal method used to determine the phase shift. With a binary code, the binary bits can determine whether the signal will be shifted to an in-phase or 180° out-of-phase condition with respect to the reference. Pulse compression of the encoded waveform involves decoding the phase shifts and comparing this to the stored code. By making a bit-by-bit comparison of the received signal to the transmitted signal, target detection can be determined at the point when the bits match. This type of circuit is known as a *matched filter.*

Figure 4-78 shows the reference signal in waveform number (1). The phase of the transmitted pulse (2) is in phase with the reference when the binary code (3) is a binary 1 and 180° out of phase when the binary code is a zero. The local oscillator signal (usually from a frequency synthesizer) is in phase with the reference and mixed with the return rf echo signals. The resulting IF signal target echoes (4) will still retain the phase coding that the transmitted pulse contained. The binary code can consist of as many bits as the transmitter pulsewidth and clock will allow. The clock frequency will determine the pulsewidth of each binary bit. The time duration of the binary bit is the usual limit to pulse compression. For example, if the transmitted pulsewidth were 15 microseconds and each bit were 100 nanoseconds, then there would be 150 bits and the pulse could be compressed down to 100 nanoseconds. This gives a pulse compression ratio of 150:1.

**Autocorrelation.**—The bit-by-bit comparison of the time-shifted, coded waveforms with a stored code can produce two values, one being the number of bits that match and the other the number of bits that do not match. The ideal condition is for the two values to be about equal for all conditions of time shift except when the two codes have a zero time shift. This condition, where only one comparison (zero time shift) gives a maximum value of agreements and all other

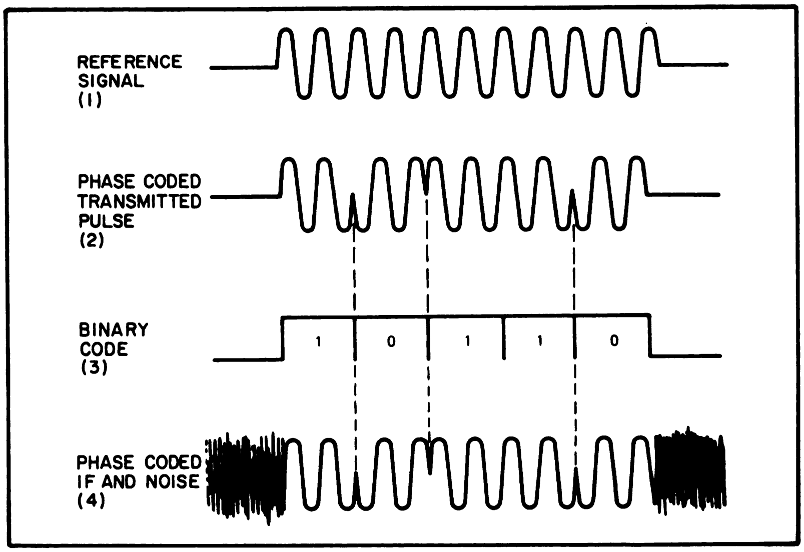
REFERENCE SIGNAL (1)
PHASE CODED TRANSMITTED PULSE (2)
BINARY CODE (3)
1
0
1
1
0
PHASE CODED IF AND NOISE (4)

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Figure 4-78.—Binary phase coding.

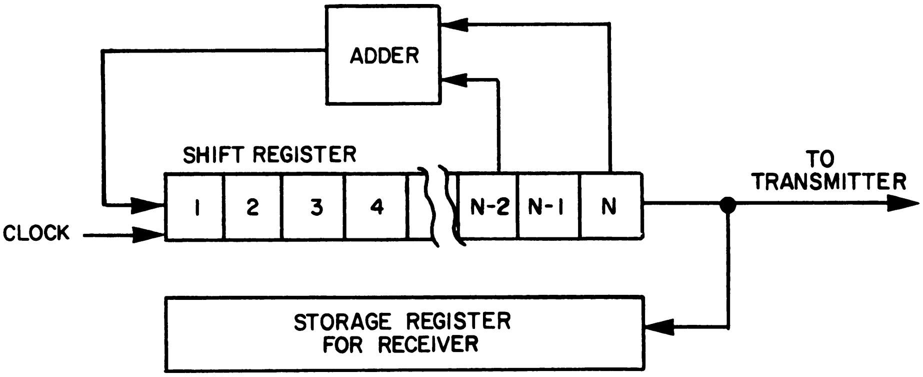

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Figure 4-79.—Pseudorandom generator.

comparisons give a minimum, is called the autocorrelation function.

**Barker Codes.**—When binary codes of 13 bits or less in length are used, only certain codes will give the optimum autocorrelation function. When the code is 5 bits long, as shown in figure 4-78, only one possible code (11101) will give an optimum autocorrelation. If the code length were increased to 13 bits, only one code (1111100110101) would exist. These optimum codes for word lengths of 13 bits or less are called Barker codes. These codes actually have two conditions—one as shown, and the other with the bit values reversed.

**Pseudorandom Codes.**—Increasing the length past 13 bits creates a different condition; no optimum words exist. However, pseudorandom sequences exist that provide optimum autocorrelation functions. A pseudorandom sequence appears random, but is actually periodic in nature and will repeat. These pseudorandom sequences are easily obtained with shift-register generators and certain feedback paths.

In figure 4-79, a representative pseudorandom generator is shown. The shift register is initially loaded with some value other than zero. The shift register is then shifted at the clock rate. Two stages are added, and the adder output determines what the first bit of the shift register is set to. The adder sets the shift register's first bit to a 1 with a 1 output. The adder has a 1 output when either shift register stage n-2 or n is a 1, but not both. This is equivalent to an exclusive OR function. A shift register with seven stages could produce a maximal code length of 127 bits and 18 possible sequences when stages six and seven of the shift register are fed to the adder. By using a maximal code, the radar receiver can be set for optimum bandwidth and pulse compression.

**DIGITAL MATCHED FILTERS.**—The matched filters required for tracking radars vary with the receiver channel function. The range channel must be able to decode and compress the phase-coded pulse and produce a narrow pulse of video when the proper code is received. The storage register in figure 4-79 stores the transmitted code for the receive interval, and the code is compared with the received signal code.

In figure 4-80, a widely used method of decoding the received pulse at video frequencies is shown. The IF signal is mixed in the phase detectors with the two IF oscillator signals to produce two video signals containing the binary phase code. (The phase detector output is high for in-phase and low for out-of-phase inputs.) The in-phase (I) channel and the 90-degree, out-of-phase (quadrature - Q) channel video signals are fed to the identical digital-matched filters by way of low-pass filters. The video signal is processed in quadrature to compensate for phase-shift variations in the received signals. The I and Q video signals out of the low-pass filters propagate through the matched-filter shift registers as they are received. In both matched filters, the received code is sequentially compared with the stored code, and an output is produced dependent upon the number of bits in correspondence. The larger the number of bits in the code, the narrower the output with maximum correspondence. In figure 4-81, two different summed matched-filter outputs are shown. The narrow, top waveform has one-tenth the pulsewidth of the lower by using 10 times the number of bits in the binary code for the same transmitted pulsewidth.

**ANGLE ERROR DETECTION.**—With tracking radars using phase-coded pulse compression, extraction of the angle error is also required. Monopulse radar receiver angle error information is contained in the phase difference between the sum (range) and difference (angle) channels, as previously discussed. Before the phase difference can be determined, the phase coding must be

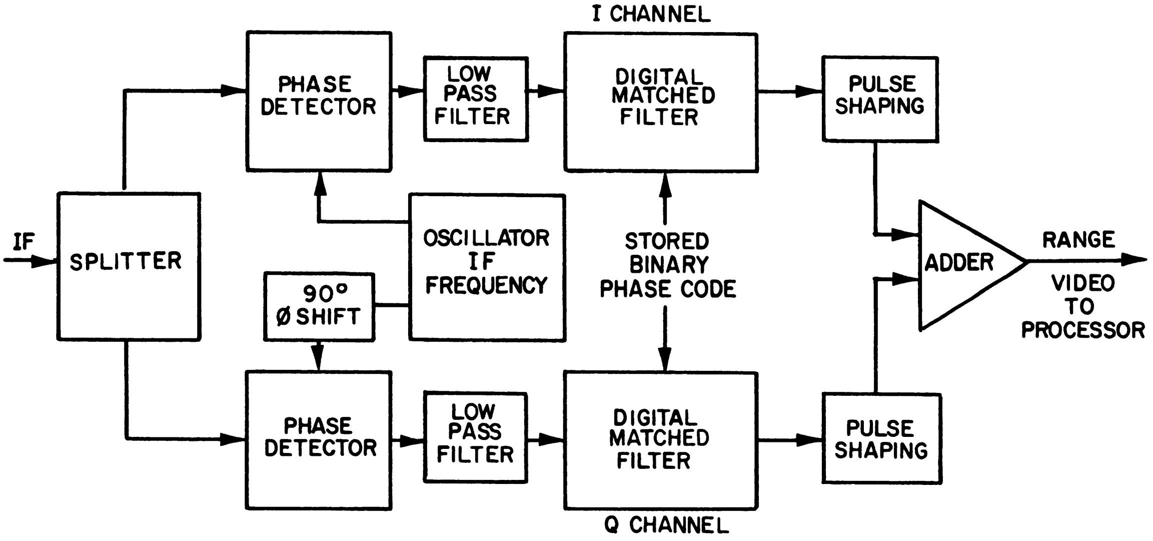

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Figure 4-80.—Quadrature receiver channel.

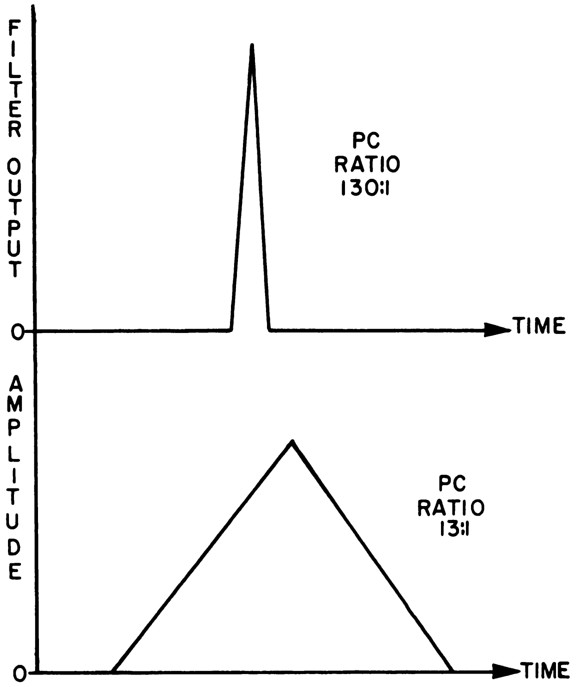

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Figure 4-81.—Digital matched filter combined outputs.

removed. Figure 4-82 shows the basic process required to extract the angle error information. The IF signal from both angle channels and the range channel is equalized in IF limiters (log-IF amplifiers). The phase coding is removed by switching the output phase of the signal decoder with the binary phase code during the range gate interval. Phase coded IF signals in correspondence with the range gate and binary phase code will produce a decoded signal as shown. Other signals, more than 1 bit out of correspondence, will have their code changed. The decoded signal will then be fed to the narrow band filter. The decoded signals have a much narrower bandwidth than phase-coded signals and pass through the narrow band filter. The narrow band filter will ring when a decoded signal passes through and produce a signal as shown. The output signal is then fed to a limiter to maintain equal signals in all three channels. The reference phase of the range channel is compared to the angle channel in a phase-sensitive detector. The output of the phase-sensitive detector is a dc voltage representing the amount and direction of the phase error. The angle error voltage is then

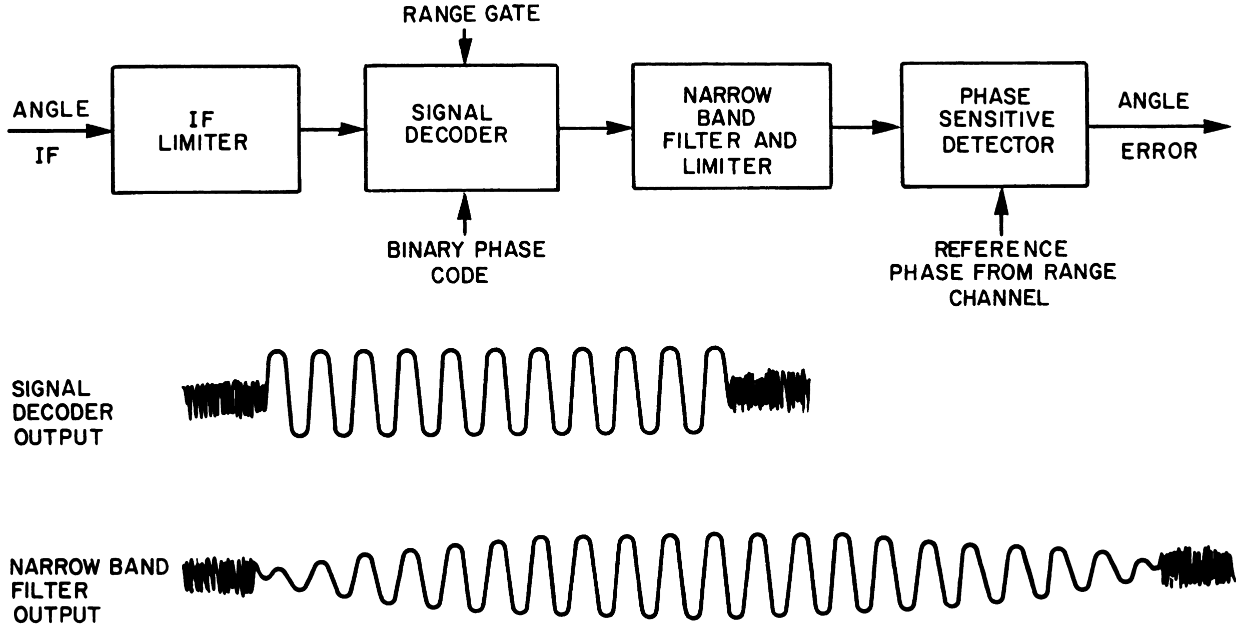

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Figure 4-82.—Angle error detection with phase-coded pulse compression.

processed to correct the antenna/director pointing error.

## RADAR DISPLAYS

Most of the radars that FCs operate and maintain have a display, or multiple displays, to provide the operator with information about the area the radar is searching or the target, or targets, being tracked. The usual display is a cathode-ray tube (CRT) that provides a combination of range, bearing (azimuth), and/or elevation data. Some displays provide raw data in the form of the signal from the radar receiver, while others provide processed information in the form of symbology and alphanumerics.

In figure 4-83, seven basic types of displays are shown. There are other variations, but these are the major types encountered in fire control and 3-D search radars.

Type A. The A sweep, or range sweep, display shows targets as pulses with the distance from the left side of the trace representing range. Variations in target amplitude cause corresponding changes in the displayed pulse amplitude. The display may be bipolar video when used with MTI or pulse Doppler radars.

Type B. The B sweep, or bearing sweep, is mostly found with gunfire control radars and would be used with surface gunfire to spot the fall of shot. The range may be full range or an interval either side of the range gate.

Type E. Two variations of type E are shown. Both provide range and elevation or height of a target. These are associated with height-finding radars and are generally used to determine the height or elevation angle only. Range would be determined from processing or a type P display.

Type F. The type F display is used with tracking radars only. The angle errors from the azimuth and elevation channels of the radar receiver would move the dot off-center with the amount and polarity of angle error. With normal tracking, the dot should stay very close to the cross hair center.

Type M. The type M is very similar to the A sweep, but it includes a movable notch or intensified area representing the range gate interval about the range gate.

Type P. This is commonly called a PPI (plan position indicator). Own ship is usually the center, and range is measured radially out from there. The range display can be selected, and the radar source is usually selectable. The PPI can be used to display raw video or symbology and alphanumerics, or both. Type P is most commonly found in CIC and in weapons control stations.

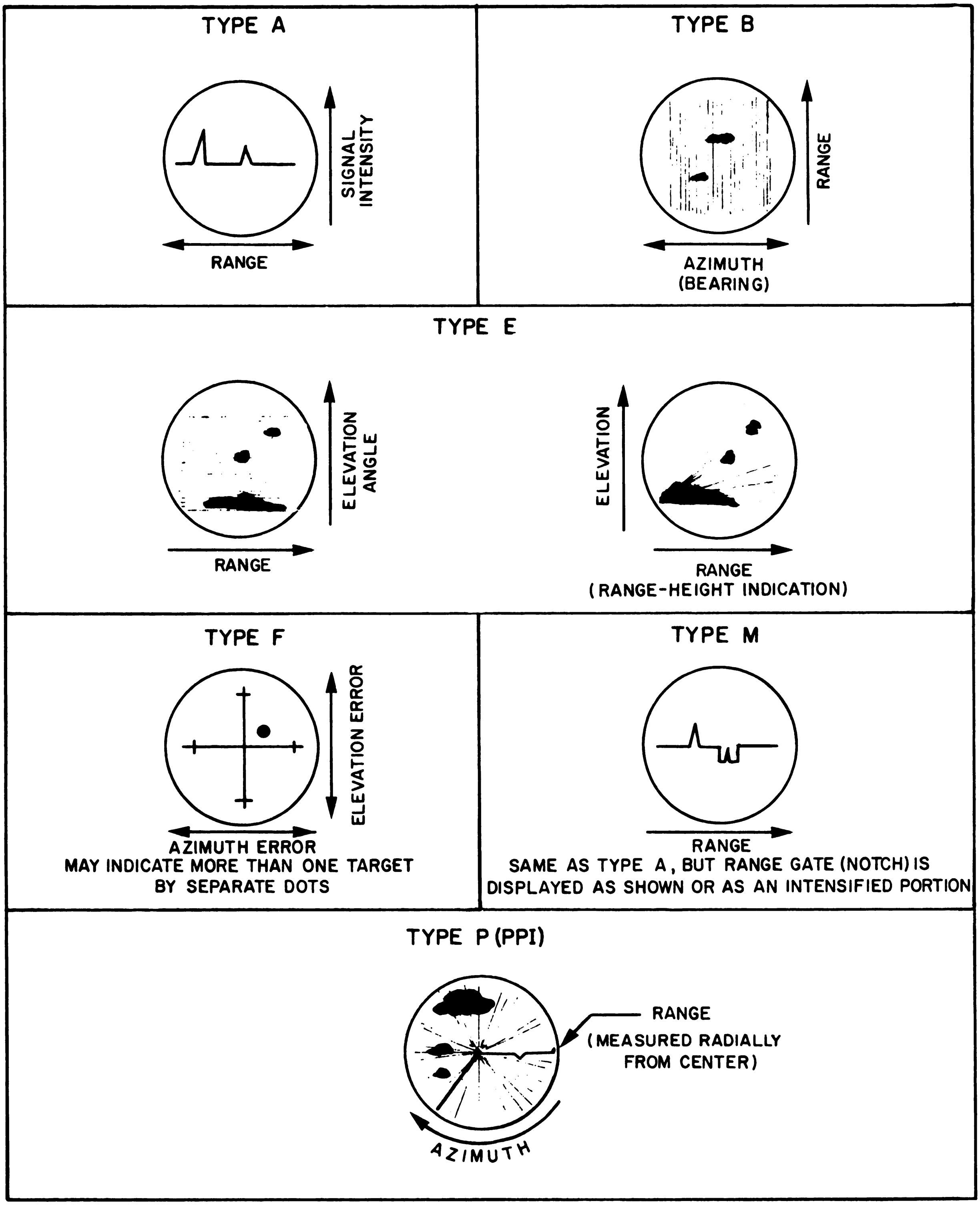
Additional reading on how individual displays are produced can be found in *Basic Electronics*, NEETS, Modules 6, 9, and 18; and the *FC3* RTM.

## ELECTRONIC WARFARE

The development of radar and its use led to the creation of the means of countering the enemy's use of their radars. The original antiradar electronic devices were called radar countermeasures and caused the development of electronic means to counter the antiradar systems, originally called antijamming. Now, the antiradar devices are called electronic countermeasures (ECM) and the antijamming devices are called electronic counter-countermeasures (ECCM). Many of the ECCM techniques in use today are derived from research and development during and immediately after World War II.

The use of ECM to deny the enemy use of their electronics and their use of ECCM to counter the ECM is called electronic warfare (EW). Electronic warfare not only encompasses radars, it also includes communications, passive detection, electronic intelligence, and electromagnetic compatibility (EMC).

As a Fire Controlman, you should be thoroughly knowledgeable in the ECCM, ECM, and EMC areas of EW. ECCM is important since you can expect to be operating the fire control tracking and search radars in an environment that will include active use of ECM to prevent detection and tracking of hostile targets. This means you should be familiar with the ECM techniques that may be used against you, as well as what ECCM techniques will work to counter the ECM. EMC is also important, since you might be operating in close proximity to friendly units and configuring your equipment to maximize compatibility and minimize electromagnetic interference (EMI).


TYPE A
SIGNAL INTENSITY
RANGE
TYPE B
RANGE
AZIMUTH (BEARING)
TYPE E
ELEVATION ANGLE
RANGE
ELEVATION
RANGE (RANGE-HEIGHT INDICATION)
TYPE F
ELEVATION ERROR
AZIMUTH ERROR
MAY INDICATE MORE THAN ONE TARGET BY SEPARATE DOTS
TYPE M
RANGE
SAME AS TYPE A, BUT RANGE GATE (NOTCH) IS DISPLAYED AS SHOWN OR AS AN INTENSIFIED PORTION
TYPE P (PPI)
RANGE (MEASURED RADIALLY FROM CENTER)
AZIMUTH

55.414

Figure 4-83.—Types of radar displays.

## ELECTRONIC COUNTERMEASURES (ECM)

Various types of ECM attempt to cause the following effects: denial of detection; confusion or deception; delayed detection or tracking; tracking an invalid target; track overload; denial of, or errors in, target parameters; or loss of target track. ECM can be divided into two major categories: (1) denial and (2) deception. Both categories can be subdivided into active and passive.

### Active Denial ECM

In this category we have the electronic jamming devices that produce signals of various types designed to prevent our detection and tracking of targets. The terms used are descriptive of the methods used in generating rf energy to jam a radar.

- Cw jamming—The transmission of constant-amplitude, constant-frequency, unmodulated jamming signals to change the signal-to-noise ratio of a radar receiver.

- Long/short pulse—Similar to cw jamming, except the pulsed signal is used in an attempt to change the signal-to-noise ratio of a radar receiver.

- Spot noise—The generation of rf noise in a particular band or frequency channel to change the signal-to-noise ratio of a radar receiver.

- Barrage noise—The generation of wide bandwidth noise signal to block out a whole band of frequencies to change the signal-to-noise ratio of a radar receiver.

- Swept jamming—Sweeping a narrow band signal over a broadband. May be swept at a medium to fast rate to saturate a radar receiver.

- Sidelobe repeater—Jamming through a side lobe to mask the main lobe signal of a radar receiver.

### Passive Denial

These are the nonelectronic devices designed to prevent detection and tracking.

- Chaff—An airborne cloud of lightweight reflecting objects (typically aluminum foil or metallic-coated fibers) to produce clutter areas.

- Radar absorbing materials (RAM)—Special materials used to coat aircraft that absorb most of the radar signal, and, thus, reflect much less signal to the radar receiver.

### Active Deception

In this category are electronic devices used to produce false echo signals to deceive and confuse a radar receiver.

- Repeaters—Intercepts and reradiates a signal of the radar to produce erroneous target parameters or false targets by modifying the reradiated signal.

- Range and velocity gate stealers—Similar to repeater, but modifies the reradiated signal to produce a larger target and then shifts the signal in time to pull the radar's range tracker off in range. Velocity gate stealing is accomplished by modifying the reradiated signal's frequency to pull a Doppler tracker off target.

- Inverse gain—Modifies reradiated signal to change its amplitude inversely with received signal from a conically scanned radar.

### Passive Deception

Nonelectronic devices used to produce false target returns and produce confusion in the radar processor or the operator's ability to distinguish targets.

- Decoys—A device, or devices, used to divert or mislead the radar. Can be closely deployed chaff or other reflective device to confuse and deceive the radar.

- Forward dispensed chaff—Chaff that is deployed by a rocket or other device so that it begins to disperse in front of the target. The target then maneuvers in attempt to shift the radar track to the chaff.

All of the types of ECM could be encountered if attacked by a large force, but usually only selected types that the enemy believes to be the most effective against your types of radars will be encountered. Many of the newer radar systems have inherent antijamming circuitry built in, thus reducing their susceptibility to many of the types of ECM. For example, a radar using Doppler processing would be practically immune to many of the passive deception and denial devices since they tend to have a very low velocity (nearly stationary).

## ELECTRONIC COUNTER-COUNTERMEASURES (ECCM)

ECCM is actions taken to ensure the use of the electromagnetic spectrum despite ECM efforts to prevent the use of it. Even today, despite all the advances in electronics, one of the best ECCM devices is still a highly trained operator. Most radars can be set to automatically respond with certain ECCM features when an expected type of ECM is encountered. Nevertheless, this response may not be the most effective when combinations of ECM are used. Then, the skilled operator has to manually select a certain type, or types, of ECCM to produce the necessary detection and tracking.

Each radar that FCs operate and maintain has built-in and selectable ECCM features. Not all ECCM features are available for each radar, since some are applicable to pulse radar but not to Doppler and vice versa.

ECCM features can either be electronic or operational. The electronic types can be in the transmitter, antenna, or the receiver/signal processor. Operational features are usually involved with manipulation of data and use of target data from other sources.

### Transmitter ECCM

The frequency, power, PRF, and waveform are the transmitter areas of ECCM features.

- Frequency—The transmitter frequency can be varied rapidly by manual control, frequency agility, frequency diversity, multiband operation, and by operation in new bands not currently used by other radars. The more rapidly and randomly the frequency change, the more difficult to actively jam.

- Power—Increasing the power output and power-level control are the main ECCM features. A radar works on the inverse fourth power law, while a jammer has to contend with only the inverse square law. The more power a radar can output, the greater the range at which the reflected signal will be greater than the jamming signal (burnthrough).

- PRF—Many features can be employed with the PRF of a radar and the pulse itself. The PRF can be jittered, frequency modulated, staggered, randomly variable, and combinations of multiple PRFs with agility. These features make it difficult for a jammer to synchronize with in order to use repeater, range-gate and velocity-gate pulloff, or false-target generators.

- Waveform—Different waveforms are usually associated with different radars, but some radars have multiple transmitters and modes of operation. The coded waveforms for pulse compression, cw, FM-cw, and pulse-Doppler waveforms are the major ECCM features of the radar waveform. If more than one type of waveform is selectable or in use simultaneously, then jamming effectiveness is greatly reduced, since jamming that effects a pulse radar may not effect a cw radar.

### Antenna ECCM

The ECCM features associated with the antenna may seem to be more the radar type, but it would not be possible without the antenna itself. These features include monopulse, variable scan, phased array, sidelobe blanking, and sidelobe cancellation. Most of the antenna and transmitter features are active or readily detectable by the enemy, since they affect the transmitted signal, or they are visible features of the antenna.

### Receiver/Signal Processor ECCM

The most numerous ECCM features are contained in the radar receiver/signal processor.

These features are passive, and, in most cases, are relatively simple and inexpensive circuits. Digital techniques have greatly improved radar receivers and signal processors. Some of the passive ECCM features are directly related to ECCM features in the transmitter and antenna, or to the type of radar, such as MTI and pulse Doppler. Some of the more important features are discussed below.

- DICKE FIX—The *Dicke Fix* is a technique that is specifically designed to protect the receiver from fast sweep jamming. The basic configuration consists of a broadband limiting IF amplifier, followed by an IF amplifier of optimum bandwidth. The limit level is preset at approximately the peak amplitude of receiver noise; the bandwidth may vary depending on the jamming environment. This device provides excellent discrimination against fast sweep jamming without appreciable loss in sensitivity. However, strong cw jamming will seriously degrade performance because the cw signal captures the radar signal in the limiter. There are many types of Dicke Fix circuits.

- Constant false alarm rate receiver—A radar receiving process using automatic detection circuits designed to produce a constant number of erroneous target detections independent of noise level at the receiver input. CFAR techniques are intended primarily to prevent receiver saturation and overload, and to present clean video information to the display and a constant noise level to an automatic detector. A device that accomplishes the above objectives may respond to the signal-to-noise ratio rather than the absolute signal level above a fixed threshold. CFAR does not usually permit the detection of a target if the target is weaker than the jamming, but it does attempt to remove the confusing effects of the jamming.

- Logarithmic receiver—A receiver whose response approximates the logarithm of the strength of the incoming signal. A special type of receiver having a large, dynamic range of automatic gain control, which gives considerable protection against receiver saturation by strong jamming or interference signals. Useful against weather, clutter, chaff, and spot jamming.

- Matched-filter receiver—A radar receiver whose signal processing circuits are designed to discriminate against signals with characteristics different from those of the transmitted rf pulse.

- Passive angle tracking (PAT)—A target may be tracked "passively" if that target emits a jamming radar signal so that angle tracking circuits can gate the signal and track the angles of maximum signal strength.

- Sidelobe blanking (SLB)—A device that employs an auxiliary wide-angle antenna and receiver to sense whether a received pulse originates in the side lobe region of the main antenna and to gate it from the output signal if it does. This technique uses an omnidirectional or wide-angle antenna and compares relative signal strength between the omni and the radar antenna. The omnichannel (plus receiver) has slightly more gain than the side lobes of the normal channel, but less gain than the main beam. Therefore, any signal that is greater in the omnichannel must have been received from a side lobe, and is blanked.

- Sidelobe canceller (SLC)—A device that employs one or more auxiliary antennas and receivers to allow linear subtraction of interfering signals from the desired output if they are sensed to originate in the side lobe of the main antenna. This technique employs the same antenna and receiver configuration as the SLB, except that a gain matching and canceling process takes place. Extraneous signals entering the side lobe of the main antenna canceled while the targets remain.

- Side lobe suppression—The suppression of that portion of the beam from a radar antenna other than the main lobe.

- Zero-crossing counting—This CFAR technique uses a wideband limiting IF amplifier followed by a zero-crossing counter that indicates the target when the rate of crossings falls below a value determined by the reference signal. The limiting action of the wideband amplifier and the random nature of the noise permit the use of a fixed threshold-detection level that is independent of the jamming signal amplitude.

- Fast time constant—A circuit with short time constant used to emphasize signals of short duration to produce discrimination against extended clutter, long-pulse jamming, or noise.

- Integration—A circuit to store and add successive pulses, or increasing a search radar's time on a target to increase the number of pulses used for detection.

- Lin-log amplifier—An automatic gain control amplifier that operates in a linear manner for low-amplitude input signals but responds in a logarithmic manner to high-amplitude input signals.

- Logarithmic fast time constant—This device consists of a logarithmic IF amplifier followed by an FTC circuit. The LOG-FTC combination is very effective in removing variations (in the video output noise level) caused by spot noise, wideband noise, and slow sweep, noise-modulated AM jamming.

**Other ECCM**

Manual and computer-aided ECCM features vary considerably and include such features as stored rates, beam-to-beam or pulse-to-pulse correlation, acceleration limiting, and data comparison from additional sources. With the increased use of digital computers, decision making within the computer can reject impossible accelerations or maneuvers of targets and select stored rates. But even the best automatic system still needs a highly trained operator to make certain ECCM feature selections.

**ECM-ECCM Matrix**

We have discussed both ECM and ECCM with some reference to which type of ECCM feature is suited for use against certain ECM types. We will now tie both together by the category of ECM and the more effective ECCM features for that type.

1. ACTIVE DENIAL

   *Cw Jamming*

   Frequency diversity, frequency agility, fast-time constant, gain controls, pulse-width discrimination, side lobe cancellation, and passive angle track

   *Long-pulse Jamming*

   All of the above plus integration

   *Spot Noise Jamming*

   Frequency diversity, frequency agility, integration, Dicke Fix, and CFAR

   *Barrage Noise Jamming*

   Dicke Fix CFAR, log FTC, automatic video noise level, higher power, and longer time on target

   *Medium and Fast-Sweep Jamming*

   Dicke Fix CFAR, variable IF bandwidth, integration, pulse compression, and frequency agility

   *Short Pulse Jamming*

   Integration and pulse compression

   *Sidelobe Repeaters*

   PRF jitter and integration, pulse compression, and side lobe blanking

2. PASSIVE DENIAL

   *Chaff*

   MTI, Doppler radar, improved resolution (narrow beamwidth, short pulse, pulse compression), log FTC, gain controls, and low scan rate on search

   *Radar Absorbing Materials*

   Longer time on target and higher power

3. ACTIVE DECEPTION

   *Repeaters*

   Complex radar waveform, frequency diversity, frequency agility, PRF jitter and integration, and side lobe blanking

*Range and Velocity Gate Stealers*

PRF jitter, leading edge tracking, acceleration limiting, and Doppler/range rate checking

*Scan Modulation Jamming*

Monopulse and variable conical scan frequency

4. PASSIVE DECEPTION

*Decoys*

Target/decoy trajectory characteristics

*Chaff (Tracking Radar)*

Higher resolution in range and angle speedgate loop, MTI, leading/trailing edge tracking, and pulse compression

You may have noticed that not all the ECCM features previously discussed were listed. Since some features are determined by the type of radar and are inherent in the radar's design, they were not included. You should study the radar systems you work with and determine which ECCM features are available in the design and which are selectable. If an ECM simulator is part of your system, time spent operating in a simulated situation will improve your capabilities when an exercise or actual jamming does occur.

## SUMMARY

Radar is an acronym for *radio detecting and ranging*. Radars not only detect and determine a target's range, they can also determine the target's azimuth, elevation, velocity, acceleration, and course. Radars transmit electromagnetic energy and receive the echo signals reflected off a target.

- Decibels—Decibels are used extensively in radars to express power ratios. The decibel is equal to 10 times the common logarithm (base 10) of the ratio; for example, 30 dB is equal to the ratio of 1000:1.

- Frequency utilization—Using the current International Telecommunications Union (ITU), radar frequency bands are classified as UHF, SHF, and EHF for the bands of radars maintained by FCs.

- Frequency, wavelength, and velocity—The frequency of electromagnetic energy is measured in hertz (Hz). The wavelength ($\lambda$) is a measurement of 1 hertz and can be calculated by the formula $\lambda = c/f$ where c = the velocity of electromagnetic energy in free space (the atmosphere for most cases). The velocity is 161,875 nautical miles per second, or 299,793 kilometers per second.

- Wave polarization—An electromagnetic wave has three vectors—direction of propagation, electric field direction (E), and magnetic field direction (H). The three vectors are mutually perpendicular with the E vector determining the polarization.

- Basic radar principles—Radars are generally classified as search (surveillance) or fire control (tracking). The search radar is used to detect a target, and the fire control radar tracks the target to refine the target-position data. The two major scales that target range is measured in are the radar mile (2,000 yards) and the yard. The rf energy travels 2,000 yards round trip in 6.1 microseconds.

The range accuracy is limited by the pulsewidth, and the angular accuracy is determined by the antenna beamwidth. The smaller the pulsewidth and beamwidth, the better the range and angular resolution. Target radial velocity is measured directly by the Doppler frequency, but actual course and speed are computed values.

- Wave propagation—Power density varies inversely as the square of the distance from the source, and a reflected signal varies inversely as the fourth power of the distance. The rf energy is also absorbed by oxygen and water vapor in the atmosphere. The absorption is greater at sea level than higher elevations causing refraction (bending) of a radar beam at low angles. The radar horizon ($R_h$) limit is primarily determined by the height of the antenna.

- Processing and detecting echo signals—This process is dependent on the transmitter power, the antenna beamwidth and gain, and the target cross section. Increasing the transmitter power, antenna gain, and decreasing the antenna beamwidth all will increase the probability of target detection. We have no control over the target cross section, but larger targets reflect more energy and can be detected easier at greater distances. The measure of a radar's sensitivity (ability to detect small signals) is called the minimum discernable signal (MDS), usually expressed in dBm (decibels referenced to 1 milliwatt).

## RADAR SYSTEMS

There are two basic types of rf transmission used by radar systems—pulse and cw. There are other types that combine features of the two basic types, such as pulse Doppler.

- Pulse radars—A basic pulse radar consists of only a few basic components—a synchronizer/timer, transmitter, antenna receiver, and display. Pulse radars transmit an rf energy pulse and detect the received echo. Range to a target is determined by the round-trip time interval between transmission and reception. Other target parameters such as azimuth and elevation angles are determined by the antenna or beam position; and processing this target data over a period of time will give the course, speed, and future position.

- Scanning—Two basic methods of scanning are used—mechanical and electronic. Mechanical scanning moves the antenna or the feed horn to position the radar beam. This type of scanning is used in search radars, tracking radars, and nutated fire control radars. Electronic scanning is accomplished by phasing or simultaneous lobing. This type of scanning is found with monopulse and phased-array radars of both search and tracking types.

- Cw radar—The Doppler shift or frequency created when a target is moving is the principle cw radars use. The cw radars transmit a signal continuously and detect the Doppler shift caused by the radial velocity of the target. Stationary targets are usually not detected by cw radars. Range determination requires modulation of the cw signal and is not as accurate as with a pulse radar. The cw radars can detect moving targets that would otherwise be undetectable by a pulse radar.

- Pulse-Doppler radar—This radar combines the best features of pulse and cw radars. Both moving targets in heavy clutter can be detected, and their range can accurately be measured with pulse Doppler radars. Another use of the pulse-Doppler radar is the moving target indication (MTI) radar. Pulse-Doppler radars usually require coherent local oscillators for accurate velocity detection.

## TRANSMITTERS

Radars use transmitters that produce high-power rf signals to be transmitted into space to detect targets. Two basic types of vacuum-tube devices are used to produce the high-power rf—crossed-field (M) and linear-beam (O) tubes.

Crossed-field tubes—Crossed-field tubes are divided into two types: resonant (oscillators) and nonresonant (amplifiers). The most common resonant type is the magnetron. The magnetron oscillates and produces a relatively high-power signal to be radiated. The most common nonresonant crossed-field device is the crossed-field amplifier (CFA). The CFA usually will not oscillate, but it will amplify an rf signal fed into the tube. The CFA has an advantage by offering a very low impedance to an rf signal when high voltage is not applied, thus allowing transmission of rf signals through the tube. Used in chains, one or more CFAs can be controlled to produce various power levels or back-up operation if one were to fail.

Linear-beam tubes—The two most commonly used linear-beam tubes in fire control are the klystron amplifier and traveling-wave tube (TWT). The klystron amplifier operates by velocity modulation of electrons vice the interaction between magnetic fields and electrons used in crossed-field tubes. The TWTs operate similar to klystron amplifiers, but use a continuous interaction between the electrons and an rf electric field. The TWTs are used more as intermediate-level amplifiers that feed other higher power amplifiers.

Modulators—Modulators provide a source of high-voltage to high-power tubes when used in pulsed systems. Two basic types of modulators that are in common use are the hard tube and line type.

## RECEIVERS

Radar receivers amplify very small signals by large factors with minimum noise introduction so that displays and processing equipment can perform their functions. Receiver system components vary with different types of radars, but all have common functional areas. Receiver system functional areas are as follows:

Low noise rf amplifier (if used)—To amplify the rf echo signal from the antenna by way of the duplexer.

Mixer (first detector)—To convert the rf signal to an IF signal that can be amplified more readily.

Local oscillator—Source of signal to mix with the rf signal to produce the IF. The local oscillator can be a reflex klystron oscillator or a frequency synthesizer.

IF amplifier—Provides the major portion of the gain of a receiver. The gain can be variable, fixed, or logarithmic.

Second detector—Varies considerably with its function and type of radar. The second detectors can be linear, logarithmic, coherent, phase-sensitive, synchronous, matched-filter, or a balanced mixer, similar to the first detector.

Radar displays use CRTs to graphically depict target information. There are seven basic displays commonly used in fire control equipment. They are the types A, B, E (two variations), F, M, and P.

## ELECTRONIC WARFARE (EW)

Two EW categories are of importance to the Fire Controlman—ECM and ECCM.

- ECM is the enemy's active and passive measures used to prevent effective use of your radars. ECM against radars is classified into four categories: active denial, passive denial, active deception, and passive deception.

- ECCM is the active and passive measures taken to ensure effective use of the radar in the presence of ECM. The best ECCM is a highly trained operator.

# CHAPTER 5

# MICROWAVE COMPONENTS

In the last chapter we studied the principles of radar. Radars use microwave components to perform their functions. The term *microwave* refers to the short wavelength (30 cm to 0.3 mm) of the higher frequencies ($10^9$ to $10^{12}$ hertz) used by radars and some communications systems. The short wavelengths involved with the microwave frequencies are about the same size as the circuit devices used. Also, the propagation time for electrical effects from one point in a circuit to another point is comparable with the oscillating currents and charges in the circuit. As a result, low-frequency circuit analysis using Kirchoff's laws of voltage and current flow no longer works to describe the effects in microwave circuitry. Instead, the use of electric and magnetic fields (electromagnetic field theory) is used to describe microwave circuit operation.

Resistors, capacitors, and inductors behave according to Kirchoff's laws at low frequencies. They exhibit the properties of power dissipation, electrical energy storage, and magnetic energy storage, respectively. However, a coil of wire that is an excellent inductor at 1 MHz may be an equally excellent capacitor at 50 MHz because of the capacitance between the turns. This does not mean that the common components cannot be used at microwave frequencies. Instead, the design and construction may be in a much different form because of the frequency dependence of the devices. Many other devices, such as vacuum tubes and transmission lines, either do not work at all or must take on a completely different form so they can function efficiently at the higher frequencies. A good example is the high-power tubes discussed in chapter 4.

The use of microwaves in radars arose from the need to focus rf energy into narrow beams. For example, a parabolic reflector with a diameter of about 3 feet (90 cm) can focus a 10-GHz (3 cm) signal into a 4.7-degree beam (common in 2D search radars). A 100-MHz signal requires a parabolic reflector about 300 feet in diameter. By comparing the size of antennas, you can see that the lower frequency would require an antenna too large for practical use on a ship or aircraft. Newer developments in antenna design have reduced the physical size of antennas, but the majority of the radars use the higher frequencies.

This chapter describes waveguide transmission lines, waveguide devices, ferrite devices, and antennas. All Navy fire control radars use microwave devices, and, as a Fire Controlman, you should understand how they work.

## WAVEGUIDE THEORY OF OPERATION

A waveguide is a metallic pipe that is used to transfer high-frequency, electromagnetic energy. Fundamentally, there are two methods of transferring electromagnetic energy. One method is by means of current flow through wires. The other is by movement of electromagnetic fields. The transfer of energy by electromagnetic field motion and by current flow through conductors may appear to be unrelated. However, by considering two-wire lines as elements that guide electromagnetic fields, the current flowing through the conductors may be considered to be the result of the moving fields.

At microwave frequencies, a two-wire transmission line is a poor means of transferring electromagnetic energy because it does not confine electromagnetic fields in a direction perpendicular to the plane that contains the wires. This results in energy escaping by radiation, as shown in figure 5-1. Electromagnetic fields may be completely confined when one conductor is extended around the other to form a coaxial cable. Figure 5-2 shows this.

Energy in the form of electromagnetic fields may be transferred very efficiently through a line that does not have a center conductor. The type of line used for this purpose is a *waveguide*. The field configuration in a waveguide is different from that in a coaxial cable because of the missing conductor. Waveguides may be rectangular, circular, or elliptical in cross section.

The three types of losses in rf lines are *copper* ($I^2R$) *losses, dielectic losses*, and *radiation losses*. The conducting area of a transmission line determines the amount of copper loss. Dielectric losses are due to the heating of the insulation between the conductors of a transmission line. Radiation losses are due to the radiation of energy from the line.

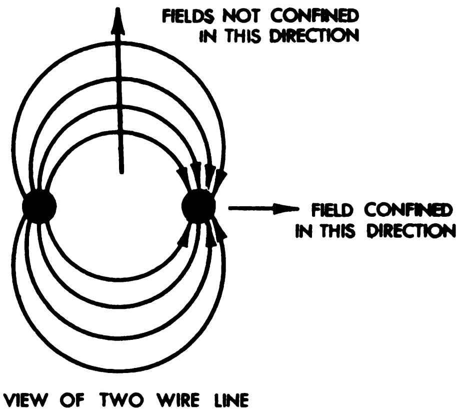

FIELDS NOT CONFINED IN THIS DIRECTION
FIELD CONFINED IN THIS DIRECTION
END VIEW OF TWO WIRE LINE

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Figure 5-1.—Fields confined in two directions but not in the other two.

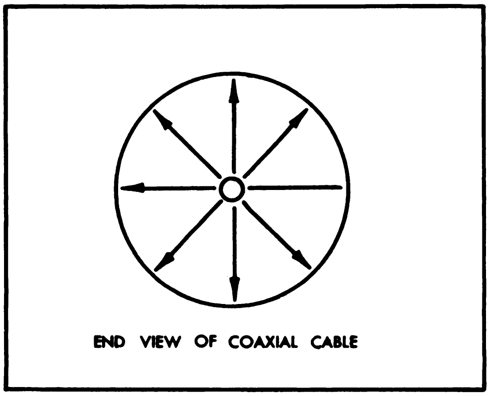

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Figure 5-2.—Fields confined in all directions.

With the above facts in mind, we will discuss the advantages of waveguides over two-wire and coaxial transmission lines. A waveguide has a large surface area. A two-wire line consists of a pair of conductors with a relatively small surface area. The surface area of the outer conductor of a coaxial cable is large, and the inner conductor is relatively small. At microwave frequencies, skin effect restricts the current carrying area of a conductor to a very small layer at the conductor's surface. Although energy transfer is due to electromagnetic field motion, the magnitude of the field is limited by the current carrying area of the conductor. From the above facts, it can be seen that the waveguide will have the least copper loss of the three types of transmission lines considered. Dielectric losses are very low in waveguides because there is no center conductor requiring solid dielectric supports. The dielectric in a waveguide is air, which has a very low dielectric loss. Radiation losses are negligible in a waveguide, since the electromagnetic fields are contained within the guide.

The power handling capability of a waveguide is greater than that of a coaxial cable of equal size. Power is a function of $\frac{E^2}{Z_0}$. E is limited by the distance between conductors. In the coaxial cable shown in figure 5-3, this distance is S1. In the circular waveguide shown (fig. 5-3), this distance is S2, which is much greater than S1. Therefore, the waveguide is able to handle greater power before the voltage exceeds the breakdown potential of the dielectric.

In view of the advantages of waveguide transmission line, it would appear that the waveguide should be the only type of line used. However, waveguides have certain disadvantages, which makes them practical only at extremely high frequencies.

The width of a waveguide must be approximately a half-wavelength at the frequency to be propagated. A waveguide for use at 1 megahertz would have to be about 700 feet wide. At 200

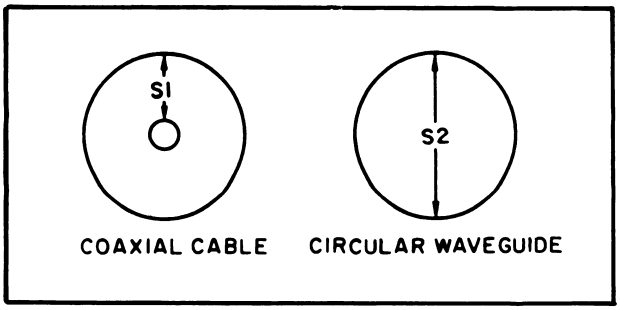

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**Figure 5-3.—Comparison of spacing in coaxial cable and circular waveguide.**

MHz, the required width would be about 4 feet. At 10 GHz, a width of only about 1 inch is required. Thus, the physical dimensions required of a waveguide make the use of this type of transmission impractical below approximately 1,000 MHz. If the width of the waveguide is less than a half-wavelength at a certain frequency, energy at that frequency, and all other frequencies below it, will not travel down the guide. There is also an upper limit to the operating frequency. Therefore, the frequency range of any system using waveguides is limited to a band of frequencies.

The installation of a waveguide system is carefully designed. The ideal situation would be one continuous section of waveguide between transmitting and receiving points. In practice, however, sections of waveguide must be connected together to form the complete line; this requires special couplings. To reduce skin effect losses, the inside surfaces of a waveguide are often plated with gold or silver. These requirements increase the cost and decrease the practicality of a waveguide system at any but microwave frequencies.

## DEVELOPMENT OF WAVEGUIDES FROM PARALLEL LINES

Figure 5-4 shows a section of a two-wire transmission line supported on two insulators. The insulators may be made of plastic, porcelain, or similar material. From the viewpoint of the line, the insulators must present a very high impedance to ground. If the insulators act as a low impedance, the line would be short-circuited or bypassed to ground. At very high frequencies, the porcelain insulators are not satisfactory because they no longer present a high impedance to ground. A superior, high-frequency insulator is a quarter-wave section of rf line short-circuited at one end. Such an insulator is shown in figure 5-5. The impedance of a short-circuited, quarter-wave section of rf line is very high at the open end (the junction of the two-wire line). This type of insulator is known as a metallic insulator and may be placed anywhere along a two-wire line.

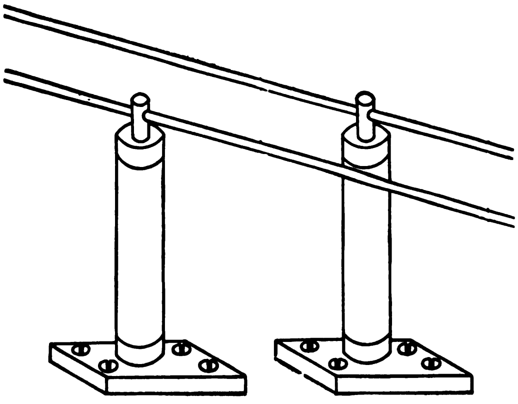

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**Figure 5-4.—Two-wire transmission line using ordinary insulators.**

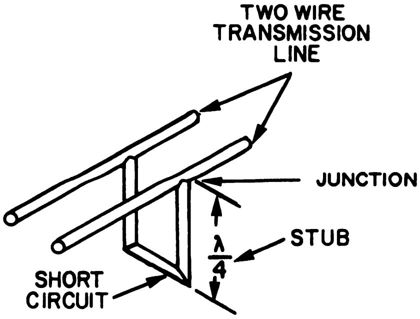

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**Figure 5-5.—Quarter-wave section of rf line short circuited at one end.**

Figure 5-6 shows several metallic insulators on each side of a two-wire line. Note that the insulators are a quarter-wavelength at only one frequency. This severely limits the broadband efficiency of this type of two-wire line.

The addition of each quarter-wave section increases the rigidity of the line. When more and more sections are added, until each section makes contact with the next, the result is a rectangular box. The line itself is actually part of the walls of the box. Thus, the rectangular box that is formed is a waveguide. This action is shown in figure 5-7. As shown in figure 5-8, the wide dimension of a waveguide (which contains the transmission line's conductors) is called the *a* dimension and determines the range of operating frequencies. The narrow dimension (or short-circuiting bar) is called the *b* dimension and determines the power handling capability of the guide.

The maximum power handled by a waveguide is directly proportional to the maximum voltage that exists between the *a* walls. In a capacitor, the working voltage is dependent upon the distance between the plates and the type of dielectric material. This same condition holds true for waveguides. Thus, the narrow or *b* dimension will determine the voltage handling capability. In figure 5-8, the *b* dimension of waveguide 2 is twice that of waveguide 1. Therefore, twice as much voltage can exist across waveguide 2 than can exist across waveguide 1. Since power is a function of the square of voltage, the power handling capability of waveguide 2 will be four times that of waveguide 1.

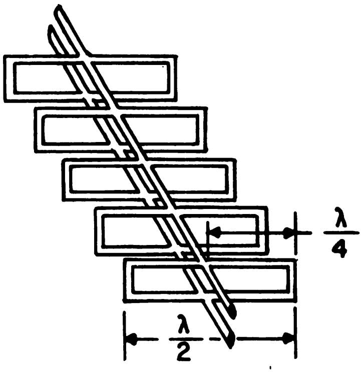

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**Figure 5-6.—Several metalic insulators on each side of a two-wire line.**

## EFFECT OF A WAVEGUIDE ON DIFFERENT FREQUENCIES

As stated previously, the use of quarter-wave metallic insulators limit waveguide operation to

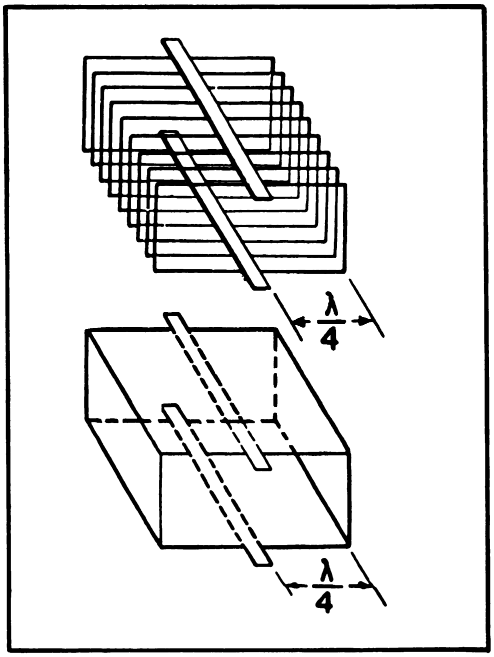

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**Figure 5-7.—Forming a waveguide by the addition of quarter-wave sections.**

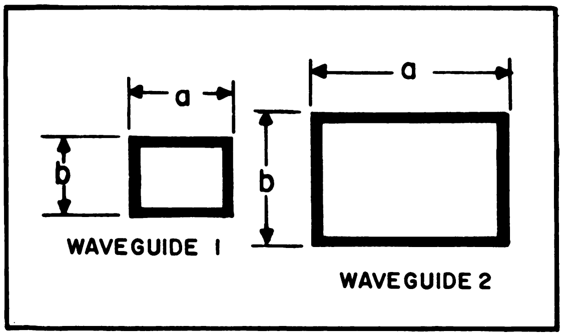

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**Figure 5-8.—Labeling waveguide dimensions.**

a single frequency. However, when a solid wall of quarter-wave insulator sections is used, the guide will operate over a small range of frequencies.

A waveguide may be considered as having upper and lower sections of metallic insulators and a central section of bus bar, as shown in figure 5-9, view A. In this figure, distance ab equals cd, which, in turn, equals 1 quarter-wavelength. Distance bc is the width of the bus bar. At some higher frequency (assuming the overall dimensions of the guide to be held constant), the required length of the quarter-wave sections decreases. In turn, the width of the bus bar is, in effect, increased in figure 5-9, view B. Theoretically, the waveguide could function at an infinite number of frequencies as the length of the quarter-wave sections approaches zero. However, in practice, theoretical performance is prevented by certain other factors, which are discussed later.

Decreasing the frequency of a signal applied to a given waveguide effectively lengthens the quarter-wave sections and narrows the bus bar. Below a certain frequency, the bus bar will cease to exist because the quarter-wave sections converge. At a still lower frequency, the required quarter-wave sections become even longer and overlap, as shown in figure 5-9, view C. Now they can no longer be accommodated within the dimensions of the guide. It follows that in a waveguide there is a low-frequency limit, or cutoff frequency ($f_{co}$), below which the waveguide cannot transfer energy. The cutoff frequency, for a given rectangular waveguide, is the frequency at which the *a* dimension of the guide is 1 half-wavelength. The *a* dimension of most waveguides is made 0.7 of the desired cutoff frequency wavelength. This allows the waveguide to handle a small range of frequencies both above and below the designed center frequency. The narrow or *b* dimension is governed by the breakdown potential of the dielectric, which is usually air. Dimensions of 0.2 to 0.5 wavelengths are common for the *b* sides.

## ELECTROMAGNETIC FIELDS IN A WAVEGUIDE

A good working knowledge of the fields that exist in a waveguide is necessary. In a waveguide, energy is transferred by electromagnetic fields.

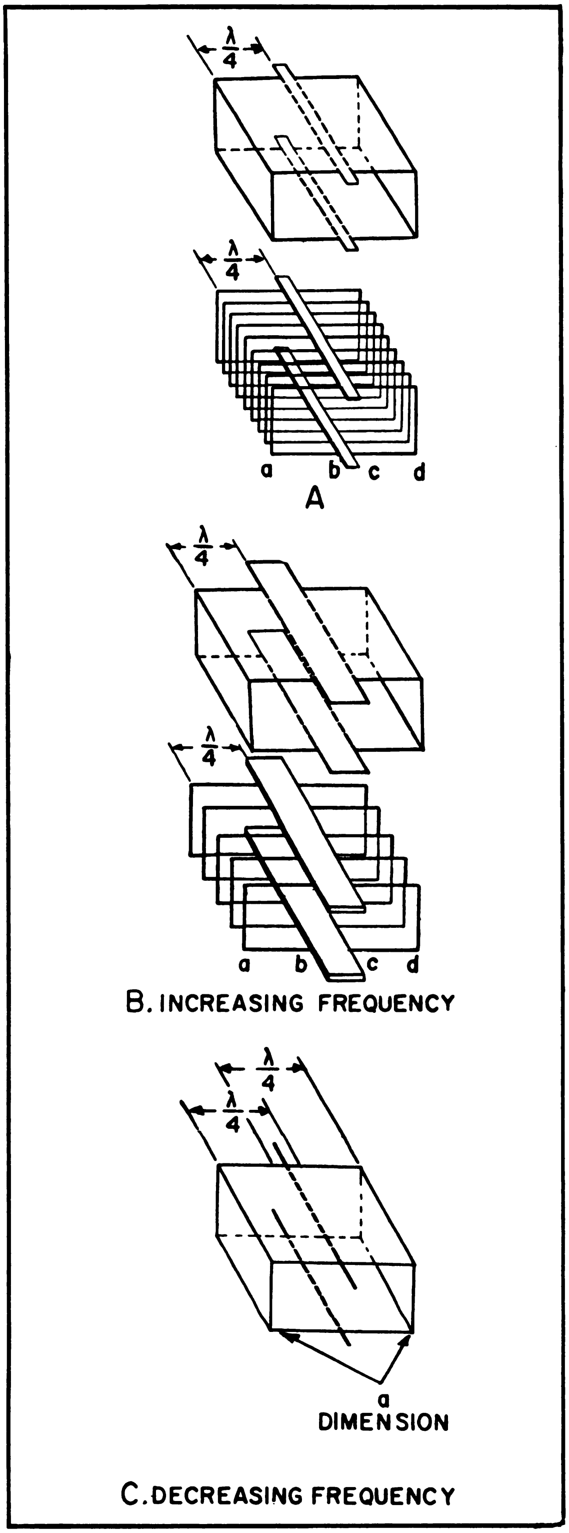

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Figure 5-9.—Frequency effects on waveguide.

The currents and voltages present are a result of the fields. In any waveguide, two inseparable fields are present. They are the *magnetic field* and the *electric field.*

### The Electric Field

The existence of an electric field indicates a difference of potential between two points. An electric field consists of a stress in the dielectric, which stores the energy of the field and is represented, in diagrams, by arrows. The simplest form of electric field is the field that forms between the plates of a capacitor, as shown in figure 5-10, view A. When the top plate of the capacitor is made positive with respect to the bottom plate, electrons move from the top plate to the bottom plate through the external circuit. This sets up a stress in the dielectric between the plates. This stress is represented by arrows pointing from the more positive point toward the more negative point.

In representing electric fields, the number of arrows indicate the relative strength of the field. In the case of the capacitor shown in figure 5-10, view A, note that the arrows are evenly spaced across the area between the two plates because the potential across the plates is equally distributed. This set of lines represents an electric field.

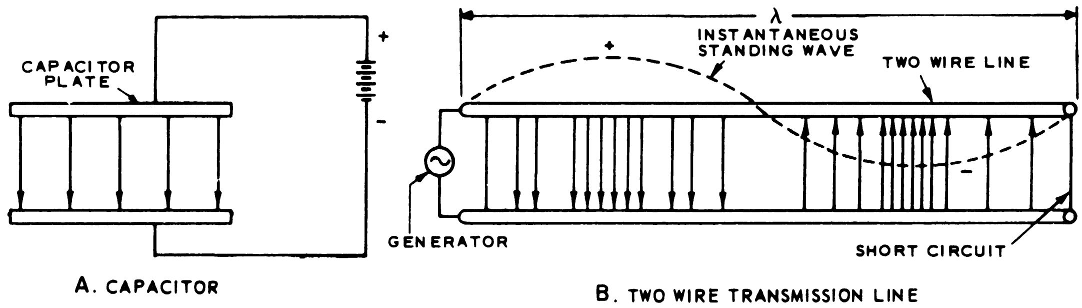

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Figure 5-10.—Representing electric fields.

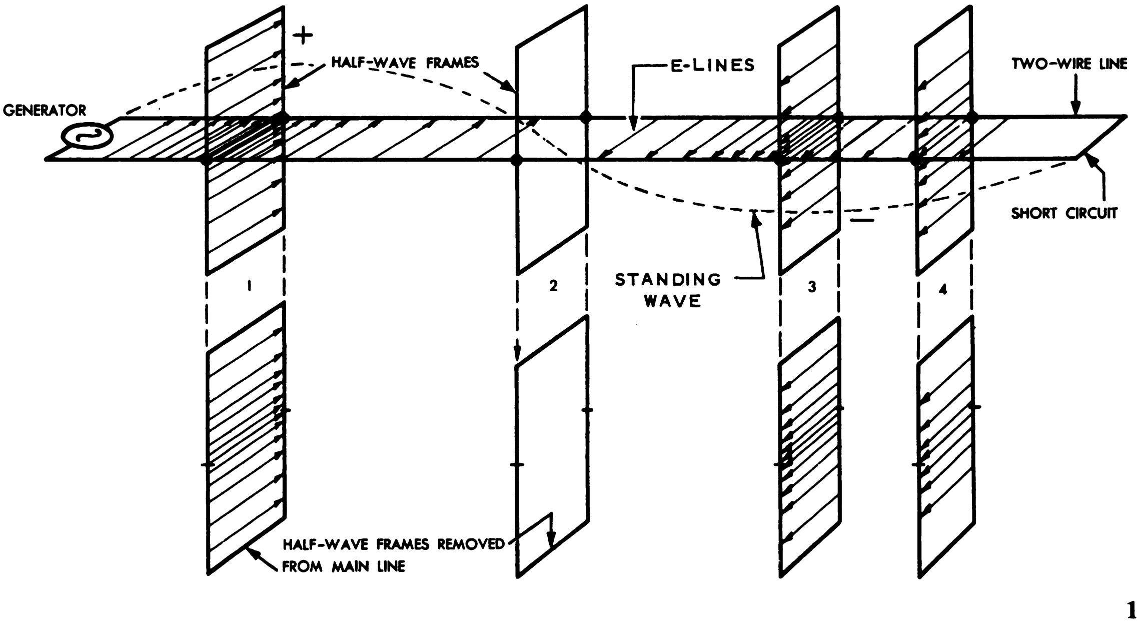

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Figure 5-11.—E-fields on two-wire line with several half-wave frames.

Electric field is abbreviated E-field, and the lines of stress are called E-lines.

The two-wire transmission line, shown in figure 5-10, view B, has an instantaneous standing wave of voltage applied to it by the generator. The line is short circuited at 1 wavelength. The instantaneous E-field strength is the same at the positive and negative voltage peaks, but the arrows, representing each field, point to opposite directions. The voltage across the line varies sinusoidally. Therefore, the density of the E-lines varies sinusoidally.

An easy way to show the development of the E-field in a waveguide is with the use of a two-wire line separated by quarter-wave metallic insulators. Figure 5-11 shows a two-wire line with several double quarter-wave insulators, or half-wave frames, used as insulators. The E-field on the main line is the same as that on the transmission line of figure 5-10, view B. The half-wave frames located at points of high voltage will have a strong E-field across them. The half-wave frames located at planes of minimum voltage will have no E-field across them.

Frame No. 1 in figure 5-11 is an example of an insulator section that has a strong E-field across it. Frame No. 2 is at zero voltage plane and has no field across it. Frame No. 3 also has a strong field, but it is of the opposite polarity. Frame No. 4 has a weaker field across it. Each frame is also shown below the main line for clarity. This illustration is a buildup to the three-dimensional aspect of the full E-field in a waveguide.

Figure 5-12, view A, shows the E-field of a voltage standing wave across a 1-wavelength section of waveguide, which is shorted at one end. The E-field is strong at one-quarter and

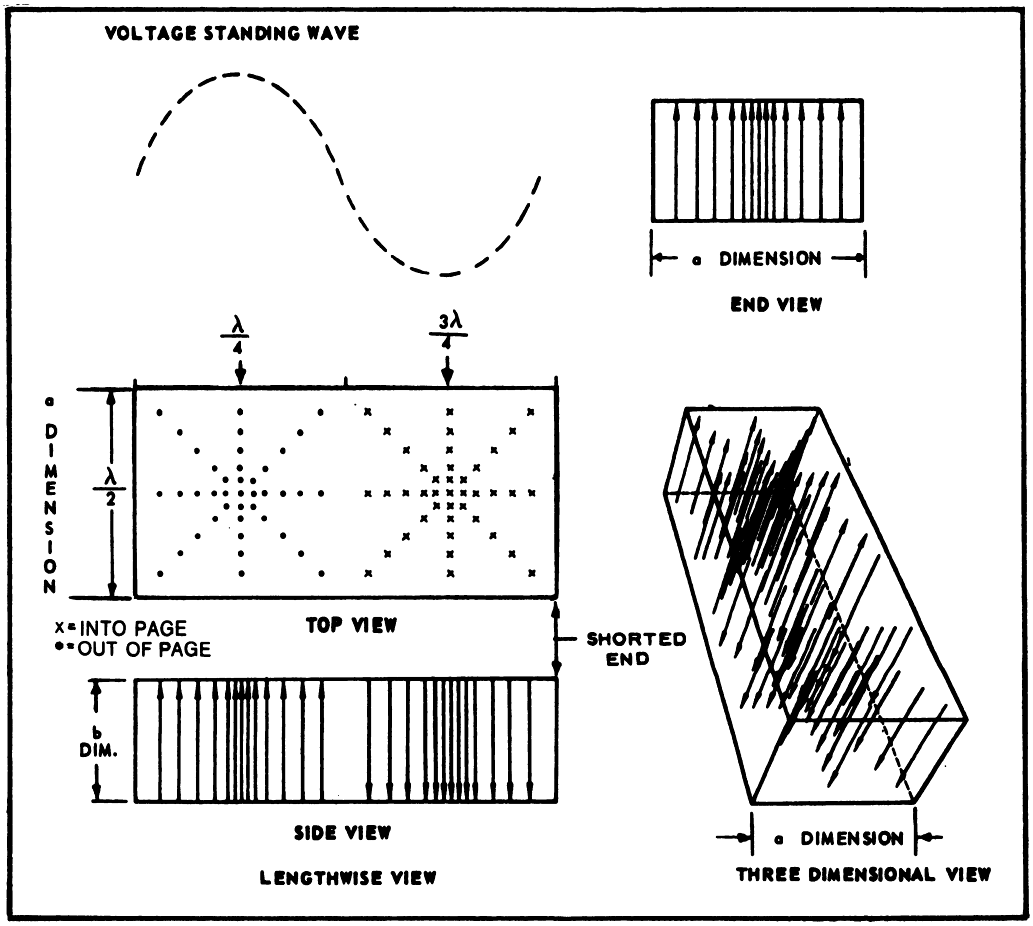

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Figure 5-12.—E-field of a voltage standing wave across a 1-wavelength section of waveguide.

three-quarter distances from the shorted end. It becomes weaker, at a sine rate, toward the upper and lower ends and toward the center. You should realize that this is an instantaneous illustration representing the instant that the standing wave is at its peak. At other times, the voltage and E-field vary from zero to the peak value, reversing polarity every alternation of the input. Note that the end view (fig. 5-12, view B) shows the field is maximum at the center and minimum near the walls of the waveguide. Figure 5-12, view C, shows the three-dimensional aspect of the E-field.

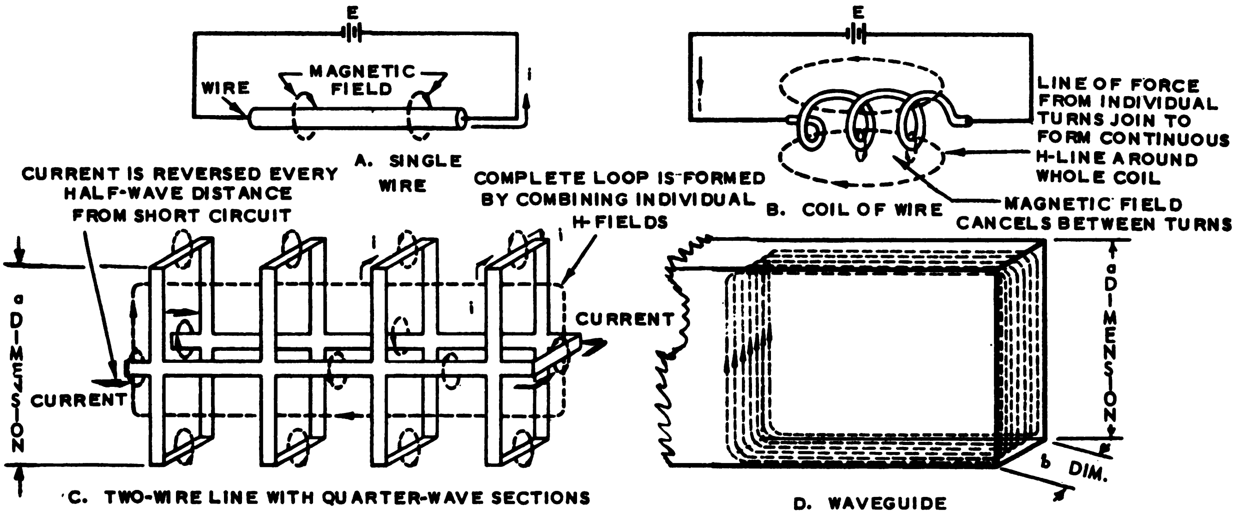
### The Magnetic Field

The second field in a waveguide is the magnetic field. The magnetic lines of force that make up the magnetic field are caused by current flow through the conducting material. The presence of the magnetic lines of force is shown by closed loops around the single wire, shown in figure 5-13, view A. The line forming the loop is a magnetic line of force, or H-line. The H-line must be a continuous closed loop to exist.

All the lines associated with current are collectively called a magnetic field or H-field. The strength of the H-field varies directly with the amount of current. Each H-line has a certain direction. This direction may be determined by the left-hand rule, which states that if the conductor is gripped in the left hand with the thumb extended in the direction of current flow, the fingers will point in the direction of the magnetic lines of force. The strength of the H-field is indicated by the number of H-lines in a given area.

Although H-lines encircle a single straight wire, they behave differently when the wire is formed into a coil, as shown in figure 5-13, view B. In a coil, the individual H-lines tend to form around each turn of wire, but, in doing so, take opposite directions between adjacent turns. This results in cancellation of the field between the turns. Inside and outside the coil, the direction is the same for each H-field. Therefore, the fields join and form a continuous H-line around the entire coil.

A similar action takes place in a waveguide. In figure 5-13, view C, a two-wire line with quarter-wave sections is shown. Current flows in the main line and in the quarter-wave sections. The current direction produces the individual H-lines around each conductor. At half-wave intervals on the main line, current flows in opposite directions. This produces H-line loops having opposite directions (the individual loops on the main line are in opposite directions). When a large number of sections exist, the fields cancel between the sections but are additive inside and outside


E
WIRE
MAGNETIC FIELD
i
A. SINGLE WIRE
E
i
LINE OF FORCE FROM INDIVIDUAL TURNS JOIN TO FORM CONTINUOUS H-LINE AROUND WHOLE COIL
MAGNETIC FIELD CANCELS BETWEEN TURNS
B. COIL OF WIRE
CURRENT IS REVERSED EVERY HALF-WAVE DISTANCE FROM SHORT CIRCUIT
COMPLETE LOOP IS FORMED BY COMBINING INDIVIDUAL H-FIELDS
a DIMENSION
CURRENT
CURRENT
i
C. TWO-WIRE LINE WITH QUARTER-WAVE SECTIONS
a DIMENSION
b DIM.
D. WAVEGUIDE

179.681

Figure 5-13.—Formation of H-lines.

the sections. Thus, they join all around the framework to form a long loop, shown in figure 5-13, view D. Outside the waveguide, the individual loops cannot join to form a continuous loop. Therefore, there is no magnetic field outside of a waveguide.

Figure 5-14 shows a conventional presentation of the magnetic field in a waveguide 3 half-wavelengths long. Note that the field is the strongest at the edges of the waveguide. This is where the current is highest. The current is minimum near the center of each set of loops because at that point the standing wave of current is zero at all times. The end view shows the field as it appears 1 quarter-wavelength (λ/4) from the end of the waveguide. Figure 5-14 represents an instantaneous condition. During the peak of the next half-cycle of the input, all field directions are reversed.

### Boundary Conditions

The travel of energy down a waveguide is similar to, but not identical to, that of the propagation of electromagnetic waves in free space. The difference is that the energy in a waveguide is confined to the physical limits of the guide. If energy is to be propagated through a waveguide, two boundary conditions must be met.

The first condition (fig. 5-15) is that an electric field must be perpendicular to a conductor

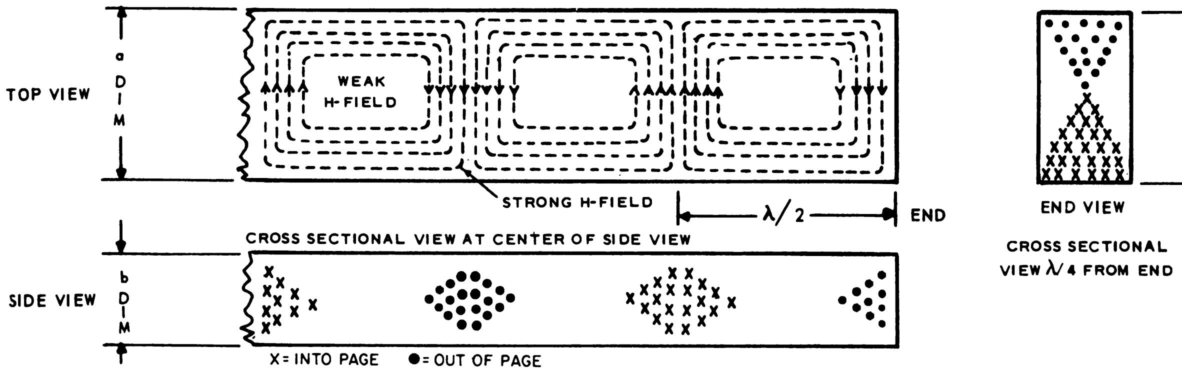


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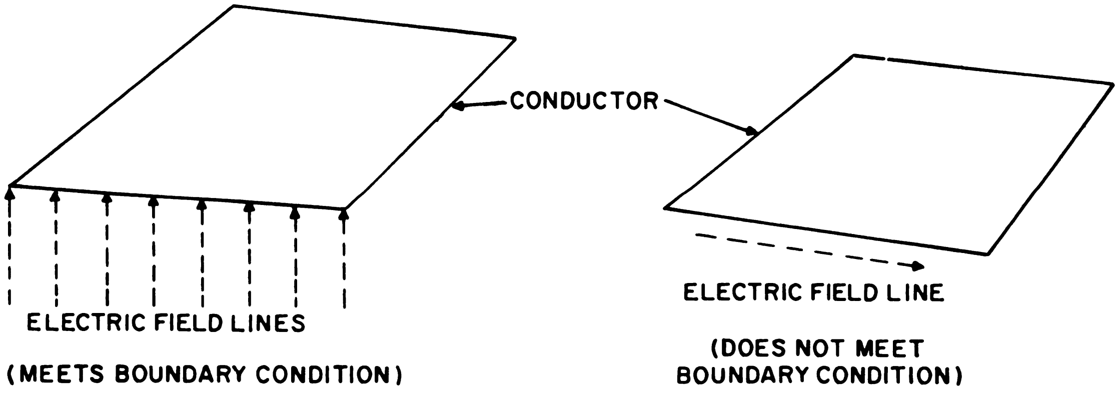
Figure 5-14.—Magnetic field in a waveguide 3 half-wavelengths long.


CONDUCTOR
ELECTRIC FIELD LINES
(MEETS BOUNDARY CONDITION)
ELECTRIC FIELD LINE
(DOES NOT MEET BOUNDARY CONDITION)

179.683

Figure 5-15.—First boundary condition.

to exist at the surface of that conductor. The converse of this statement is also true. Assuming a perfect conductor, if an electric field has a component parallel to the conductor, the electric field cannot exist at the surface of that conductor.

The second boundary condition is that, at the surface of the waveguide, there be no perpendicular component of the magnetic field. This condition is satisfied by the configuration of the magnetic field, since all the H-lines are parallel to the surface of the waveguide.

Electric and magnetic fields exist simultaneously in a waveguide. In fact, the E-field causes a current flow, which, in turn, produces an H-field. Therefore, neither field can exist alone.

## MODES OF OPERATION

Figure 5-16, view A, shows the two fields that exist in a waveguide. Details of this three-dimensional figure are amplified in figures 5-16, views B, C, and D. In these diagrams, the number of E-lines in a given area indicates the strength of the electric field; while the number of H-lines in a given area indicates the strength of the magnetic field in that area.

The field configuration, shown in figure 5-16, represents only one of the many ways in which fields are able to exist in a waveguide. Such a field configuration is called a *mode of operation*. The *dominant mode* is the easiest mode to produce. Other modes (that is, different field configurations) may occur accidentally, or they may be caused deliberately.

### Dominant Mode

The dominant mode is the most efficient mode; it has the least attenuation. Normally, waveguides are designed so that only the dominant mode will be conducted. To operate in the dominant mode, a waveguide must have an *a* dimension of at least 1 half-wavelength at the frequency to be propagated. To ensure that only the dominant mode will exist, the *a* dimension of the guide must be maintained near the minimum allowable value. In practice, this dimension is usually seven-tenths of a wavelength.

The dominant mode has the lowest cutoff frequency. This, of course, is its low-frequency

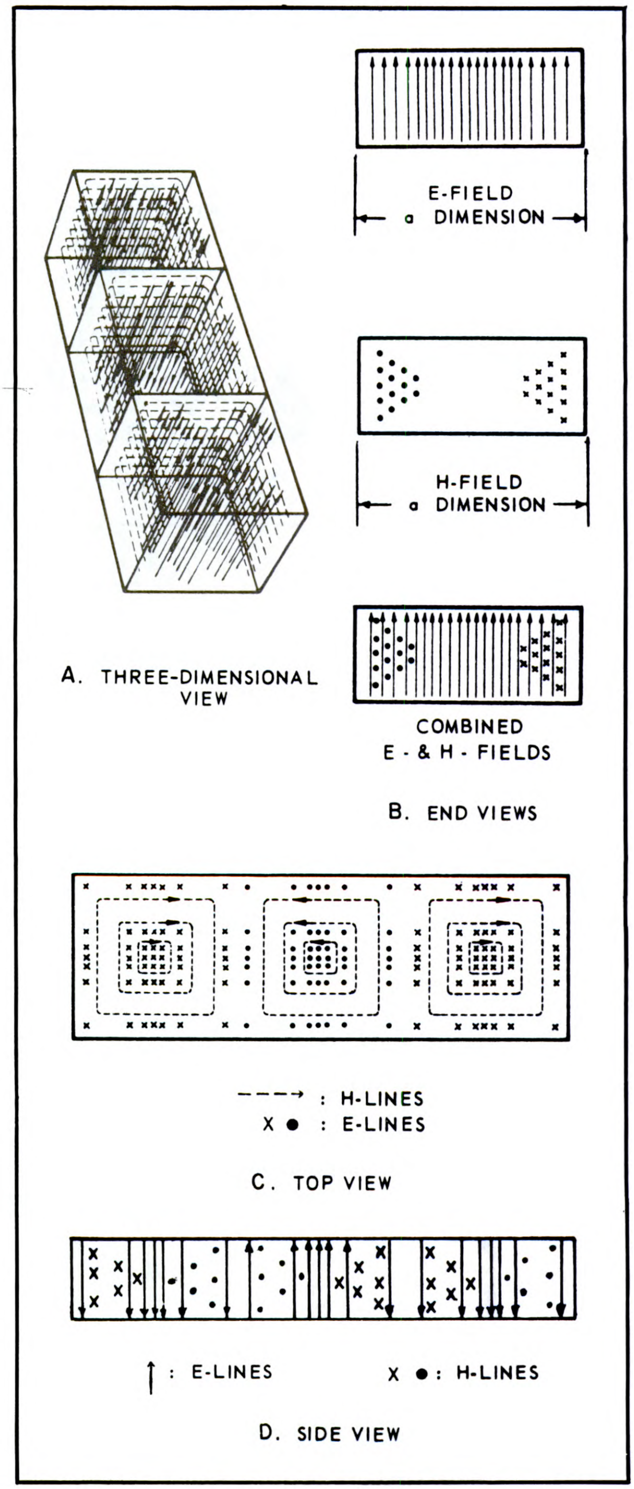


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Figure 5-16.—E- and H-fields in a waveguide.

limit. The high-frequency limit of a waveguide is a frequency at which its *a* dimension becomes large enough to allow operation in a higher mode than that for which the system was designed.

In some cases, waveguides may be designed to operate in a mode other than the dominant mode. An example of this is shown in figure 5-17. If the size of the waveguide in this figure is doubled over that of the waveguide in figure 5-16, the *a* dimension will be a full wavelength long. The two-wire line may be assumed to be a quarter-wavelength from one of the *b* walls, as shown in figure 5-17, view A. The remaining distance to the other *b* wall is three-quarters of a wavelength. The three quarterwave section has the same high-impedance input as the quarter-wave section; therefore, the two-wire line is properly insulated. The field configuration will show a full wave across the *a* dimension, as shown in figure 5-17, view B.

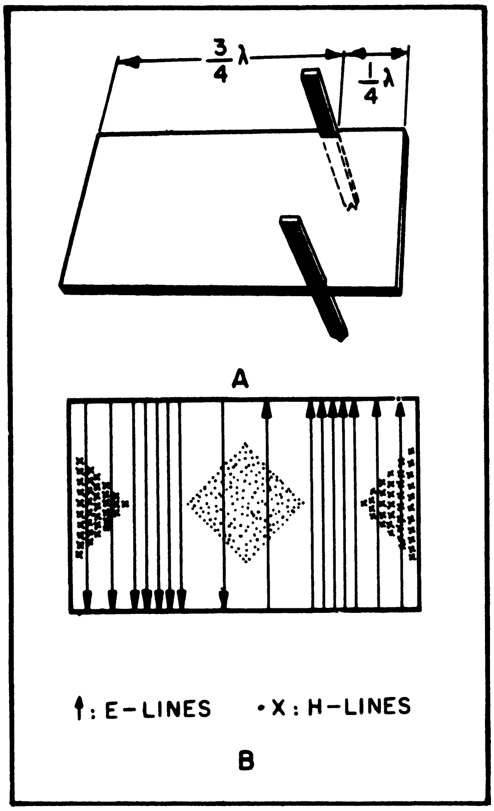

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Figure 5-17.—Operating in other than dominant mode.

Although rectangular guides are used almost exclusively in radar systems, circular and elliptical waveguides are used in specific areas. Figure 5-18 shows the dominant mode of a circular waveguide. The cutoff wavelength of a circular guide is 1.71 times the diameter of the guide. Thus, the diameter must be 2/1.71, or approximately 1.17 times the *a* dimension of a rectangular guide having the same cutoff frequency. Circular waveguides are often used in the rotating portion of a radar antenna system.

### Mode Numbering System

Thus far, only the most basic type of E- and H-field arrangement has been shown. It is sometimes necessary to have a more complex arrangement to facilitate coupling, isolation, or types of operation. To describe the various modes of operation, the field arrangements are first divided into two categories: *transverse electric* (TE) and *transverse magnetic* (TM).

In a transverse electric mode, all parts of the electric field are perpendicular to the length of the guide, and no E-field is parallel to the direction of travel. In a transverse magnetic mode, the place of the H-field is perpendicular to the length of the waveguide. No H-line is parallel to the direction of travel.

In addition to the designation TE or TM, subscript numbers are used to complete the

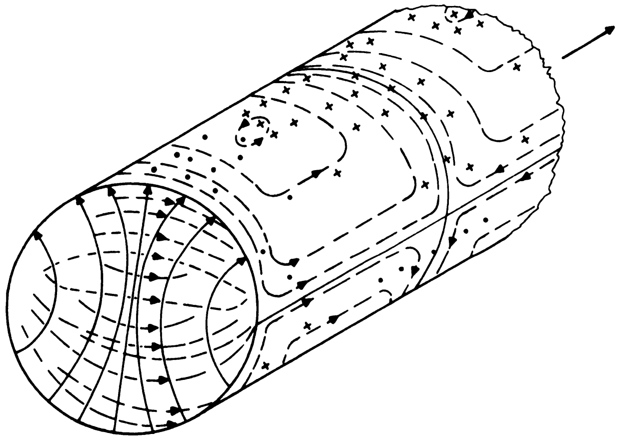

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Figure 5-18.—Circular guide showing dominant mode.

description of the field pattern. In rectangular waveguides, the first subscript indicates the number of half-wave patterns in the *a* dimension, and the second subscript indicates the number of half-wave patterns in the *b* dimension. In circular waveguides, the first subscript indicates the number of whole wavelength patterns around the circumference of the guide. The second subscript indicates the number of half-wave patterns along the diameter of the guide. Elliptical guides are numbered similar to rectangular guides except the *a* and *b* dimensions are called the major (elliptical) and minor (hyperbolic) axis.

Elliptical cross-section waveguides use a subscript preceding the TE or TM indicating even (e) or odd (o) and referring to the half-wave patterns in the elliptical and hyperbolic axis. The dominant mode for rectangular guides is designated $TE_{10}$; the dominant mode for circular guides is $TM_{01}$ because of its ease in termination; and the ${}_eTE_{11}$ mode is dominant in elliptical guides.

A method of numbering modes is by counting half-wavelengths. In the rectangular waveguide shown in figure 5-19, view A, all of the electric lines are perpendicular to the direction of movement. This makes it a TE mode. In the direction across the narrow dimension parallel to the E-line, there is no intensity change, so the first subscript is zero. Across the guide along the wide dimension, the E-field varies from zero at the top, through maximum at the center, to zero on the bottom. Since this is 1 half-wavelength, the second subscript is 1. Thus, the complete description of this mode is $TE_{01}$.

Referring to the circular waveguide in figure 5-19, view B, the E-field is transverse electric (TE). Moving around the circumference starting at the top and going counterclockwise, the fields go from zero, through maximum positive, through zero, through maximum negative, and back to zero. This is 1 full wave, so the first subscript is 1. Going through the diameter, the start is from zero at the top, through maximum at the center, to zero at the bottom. As this is 1 half-wave, the second subscript is 1, making this circular mode $TE_{11}$.

Various elliptical, circular, and rectangular modes are possible. You can verify the numbering system using the diagrams in figure 5-20. Note that the magnetic and electric fields are maximum in intensity in the same area. This indicates that the current and voltage are in phase. This condition results when there are no reflections to cause standing waves.

## BEHAVIOR OF ELECTROMAGNETIC WAVES WITHIN A WAVEGUIDE

When a small probe is inserted in a waveguide and excited with rf energy, it will act as a vertical

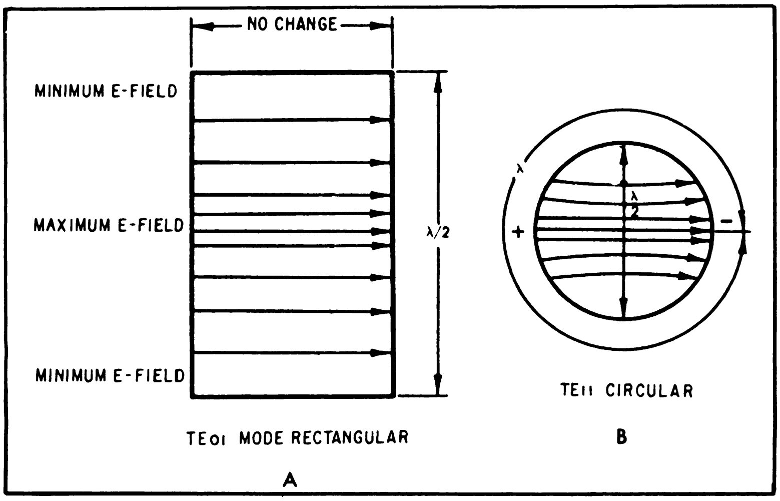

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Figure 5-19.—Numbering modes by counting wavelengths.

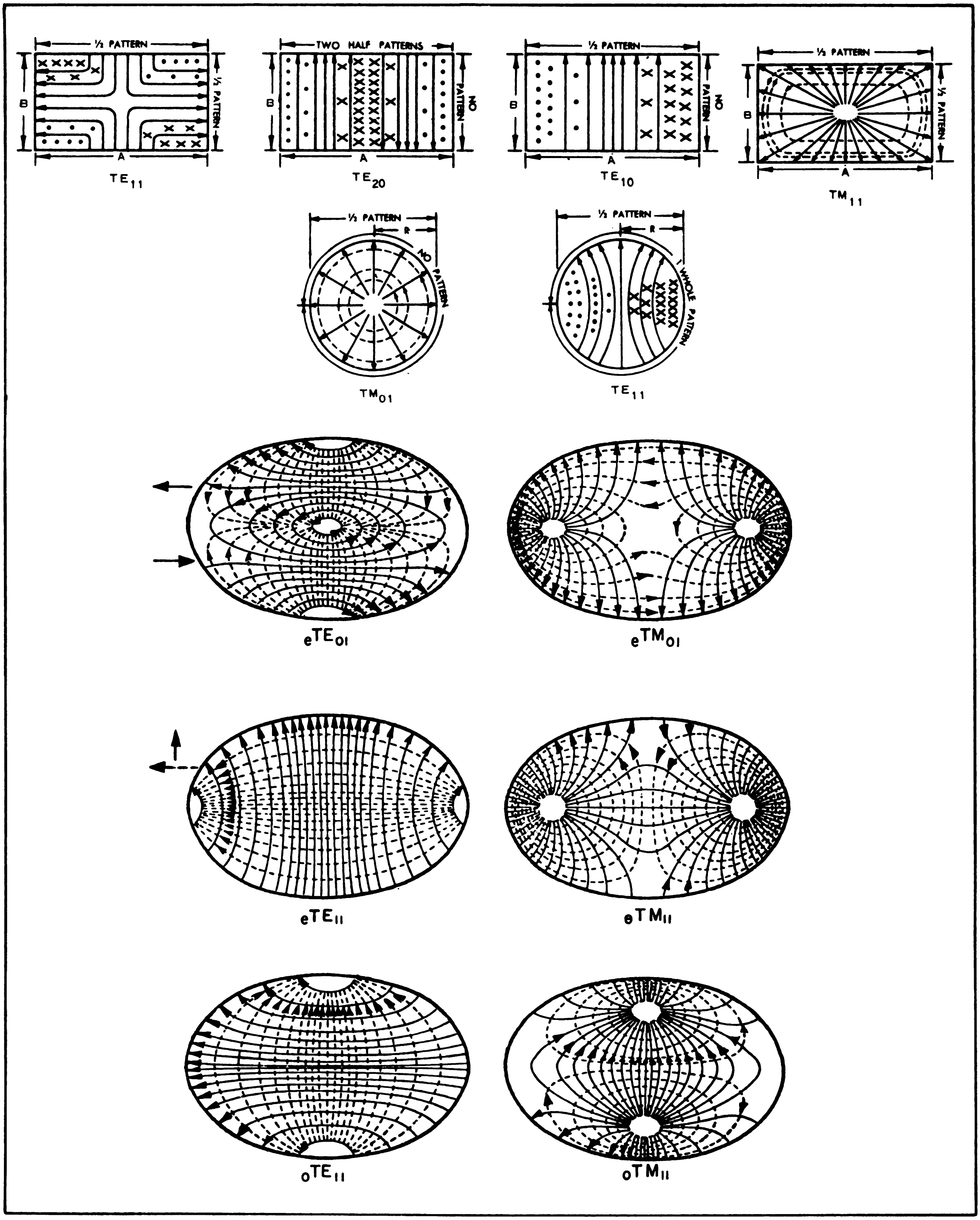

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Figure 5-20.—Various modes of operating for elliptical, rectangular, and circular waveguides.

antenna. Positive and negative wavefronts are radiated from the probe, as shown in figure 5-21.

The portion of any wavefront traveling in direction B will be rapidly attenuated because it will not fulfill the required boundary conditions.

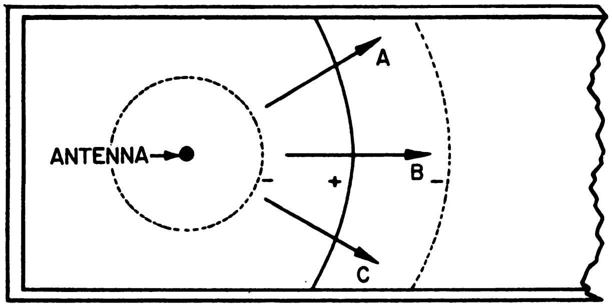

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Figure 5-21.—Radiation from probe inserted in a waveguide.

The portions of any wavefront traveling in directions A or C will resolve themselves into oblique wavefronts traveling across the guide. This action is shown in figure 5-22. Note that wavefronts of the same polarity cross at the center of the guide. This produces a maximum E-field along the center of the guide. Also, opposite polarity wavefronts meet at the walls of the guide, thereby cancelling. This causes the E-field to be zero at the walls of the guide. This fulfills the boundary conditions.

The angles between the wavefront arriving at the wall of the guide and the perpendicular to the surface at the point of arrival (*normal*) is known as the ***angle of incidence*** (Θ). The angle at which the wavefront is reflected from the wall of the of the guide and the ***normal*** is called the ***angle of reflection*** (ϕ). These angles are equal, and they are depicted in figure 5-22.

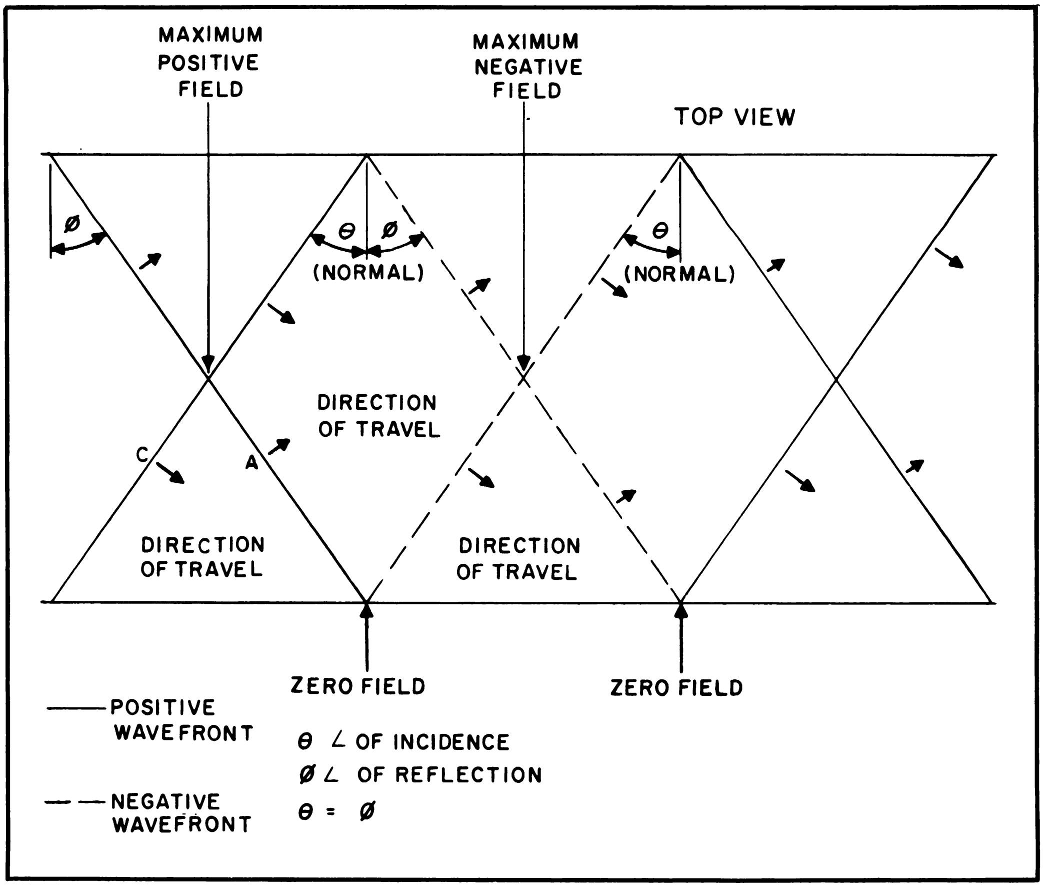

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Figure 5-22.—Wavefront travel in a waveguide.

The angles of incidence and reflection are a function of frequency (assuming the guide dimensions are held constant). Figure 5-23 shows the angles of incidence and reflection for a high frequency, a medium frequency, and a frequency just above the cutoff frequency. As the frequency being transmitted decreases, the angles decrease. Just below the cutoff frequency, the angles of incidence and reflection become zero. Therefore, at any frequency lower than $f_{co}$, the wavefronts will be reflected back and forth across the guide, setting up standing waves; no energy will be conducted down the guide.

In figure 5-23, though the wavefront is traveling at the velocity of light, it is not moving straight down the guide. Its straight line velocity or axial velocity appears to be less than the speed of light. This axial or straight line velocity is called the group velocity ($V_g$). The relationship of the group velocity to the diagonal velocity illustrates an unusual phenomenon. During a given time (fig. 5-24), a wavefront will move from point one to point two, a distance of L, at the velocity of light ($V_c$). Because of this diagonal movement, the wavefront actually has moved down the guide only a distance of G. The velocity with which the wavefront has moved through distance G is group velocity. However, if an instrument were used to detect the two positions at the wall, the positions would be a distance P apart. This distance is greater than distance L or G. Therefore, the contact point between the wavefront and the wall appears to be moving with a velocity greater than the velocity of light. Since the phase of the rf has changed over distance P, this velocity is called the *phase velocity* ($V_p$). The mathematical relationship between the three velocities is given by the equation $V_c = \sqrt{V_g V_p}$.

When a modulated rf signal is propagated down a waveguide, the modulation envelope appears to move forward at the group velocity, while the individual rf cycles appears to move forward through the envelope at the phase velocity. Nevertheless, group velocity decreases with a decrease in frequency, and phase velocity increases with a decrease in frequency. At the same time, group velocity is always less than the velocity of light by the same amount that phase velocity is greater than the velocity of light. Therefore, the overall movement of the signal is at the velocity of light.

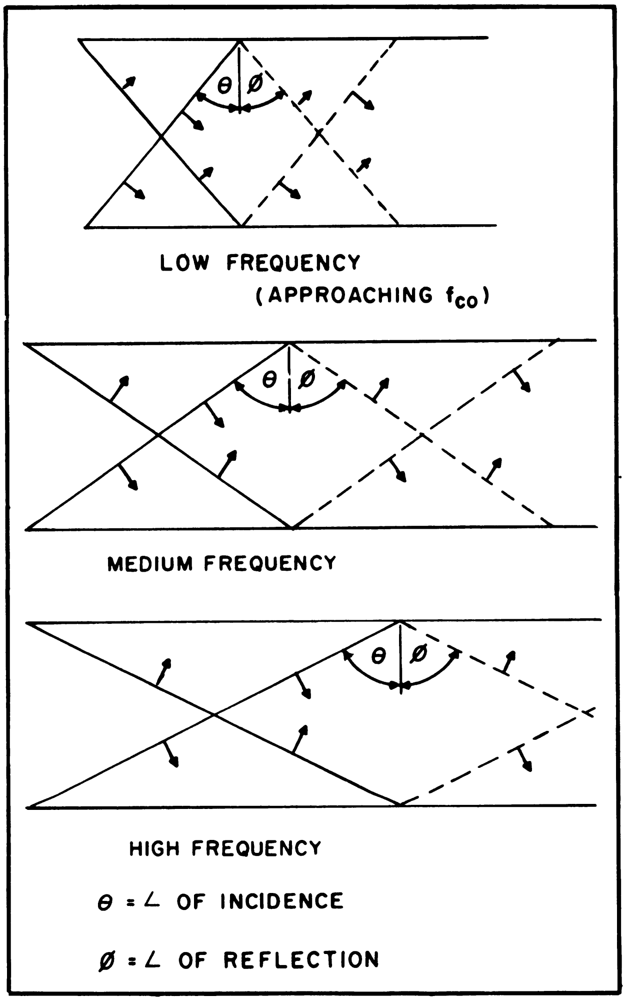

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Figure 5-23.—Effects of frequency on angles of incidence and reflection.

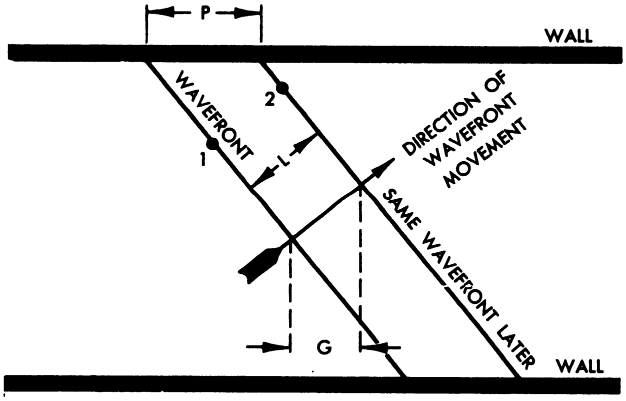

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Figure 5-24.—Relationship of group velocity to diagonal velocity.

## METHODS OF COUPLING

Fundamentally, there are three methods of coupling energy into or out of a waveguide—*probe, loop*, and *aperture*. Probe, or capacitive, coupling is shown in figure 5-25. Its action is the same as that of a quarter-wave antenna. When the probe is excited by an rf signal, an electric field is set up (fig. 5-25, view A). The probe should be located at a point in the center of the *a* dimension and a quarter-wavelength, or odd multiple of a quarter-wavelength from the short-circuited end, as shown in figure 5-25, view B. This is a point of maximum E-field; therefore, it is a point of maximum coupling between the probe and the field. Usually, the probe is fed with a short length of coaxial cable. The outer conductor is connected to the waveguide wall; the probe extends into the guide, but is insulated from it as shown in figure 5-25, view C. The degree of coupling may be varied by varying the length of the probe, removing it from the center of the E-field, or shielding it.

In a pulse-modulated radar system, there are wide sidebands on either side of the carried frequency. A wideband probe may be used to prevent the probe from discriminating too sharply against frequencies that differ from the carried frequency. This type of probe is shown in figure 5-25, view D, for both low- and high-power usage.

Figure 5-26 shows loop, or inductive, coupling. The loop is placed at a point of maximum H-field in the guide. As shown in figure 5-26, view A, the outer conductor is connected to the guide, and the inner conductor forms a loop inside the guide. The current flow in the loop sets up a magnetic field in the guide. This action is shown in figure 5-26, view B. As shown in figure 5-26, view C, the loop may be placed in a number of locations. The degree of loop coupling may be varied by rotation of the loop.

The third method of coupling is aperture, or slot, coupling. This type of coupling is shown in figure 5-27. Slot A is at an area of maximum E-field and is a form of electric field coupling. Slot B is at an area of maximum H-field and is a form

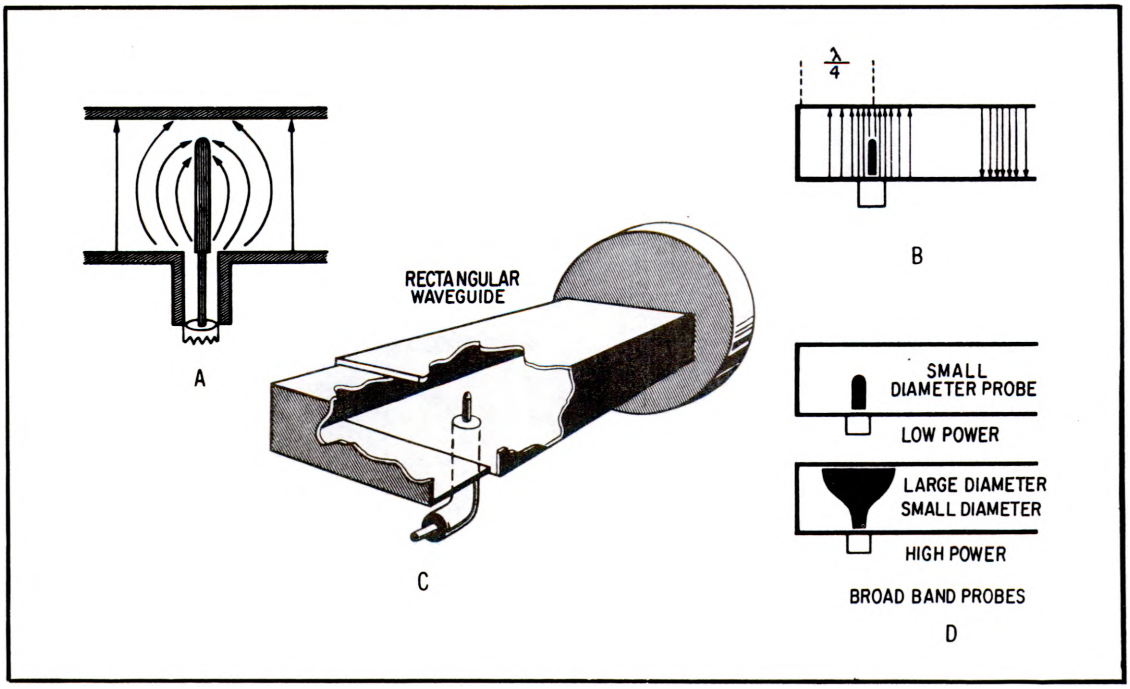

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Figure 5-25.—Probe or capacitive coupling.

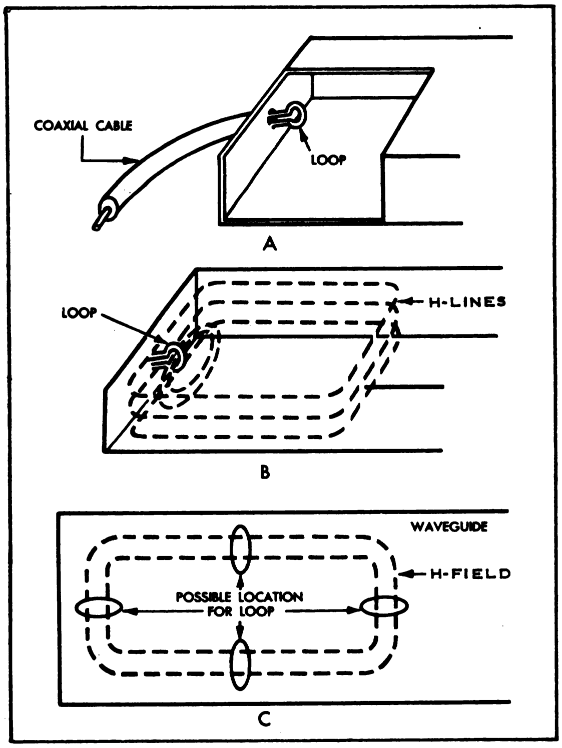

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Figure 5-26.—Loop or inductive coupling.

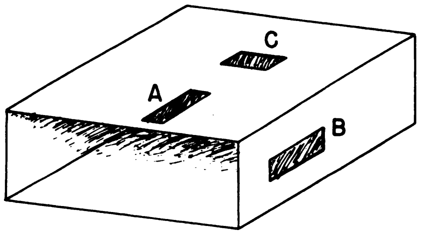

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Figure 5-27.—Aperture or slot coupling.

of magnetic field coupling. Slot C is at an area of maximum E- and H-field and is a form of electromagnetic coupling.

## BENDS, TWISTS, AND JOINTS

Any abrupt change in the size, shape, or direction of a waveguide system results in reflections. Usually, a radar system requires bends or twists in its waveguides. Bends may be made if they have a radius of at least 2 wavelengths, as shown in figure 5-28, view A. The electromagnetic field may be rotated by twisting the waveguide as shown in figure 5-28, view B. The twists must be accomplished over a distance of at least 2 wavelengths.

Sometimes a sharp 90-degree bend is required. To avoid reflections, the guide is constructed with a 45-degree section, 1 quarter-wavelength long, on the outside of the bend (fig. 5-28, view C). The combination of the direct reflection at one bend and the inverted relection from the other bend will cancel and leave the fields as though no reflection had occurred. The bend can be made in either the narrow or wide dimension of the guide without changing the mode of operation.

It is practically impossible to construct a waveguide system in one piece. It is necessary to construct guide sections, which must be connected by joints. Any irregularities in the joints cause standing waves and permit energy to be dissipated. A proper, permanent joint affords a good connection between the parts of a waveguide

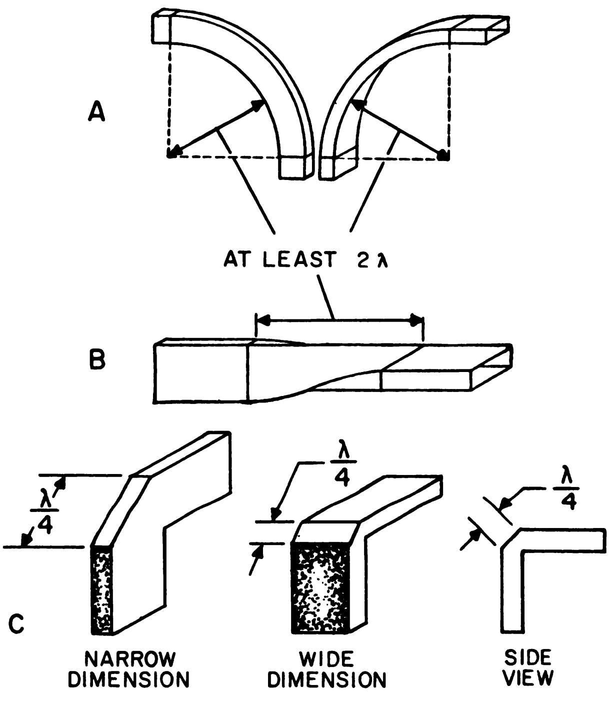

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Figure 5-28.—Waveguide bends and twists.

and has very little effect on the fields. Normally, this type of joint is made at the factory. When it is used, the waveguide sections are machined within a few thousandths of an inch and then welded together. The result is a hermetically sealed and mirror-smooth joint.

Where sections of waveguide must be taken apart for normal maintenance and repair, it is impractical to use a permanent joint. To permit portions of the waveguide to be separated, the sections are connected by semipermanent joints, of which the choke joint is the most common type. Cross-sectional views of a choke joint are shown in figure 5-29, views A and B. It consists of two flanges that are connected to the waveguide at the center (fig. 5-29, view C). The right flange is flat, and the one at the left is slotted 1 quarter-wavelength deep from the inner surface of the waveguide, at a distance of 1 quarter-wavelength from the point where the flanges are joined. The quarter-wavelength slot is short circuited at the end. The 2 quarter-wavelength sections form a half-wavelength section and reflect a short circuit at the place where the walls are joined together.

Electrically, this creates a short circuit at the junction of the two waveguides. The two sections may actually be separated as much as a tenth of a wavelength without excessive loss of energy at the joint. This separation allows room to seal the interior of the waveguide with a rubber gasket for pressurization. The quarter-wave distance from the walls to the slot is modified slightly to compensate for the slight reactance introduced by the short space and the open circuit from the slot to the periphery of the flange. The loss introduced by a well-designed choke is less than 0.03 dB, while a well-machined, unsoldered, permanent joint, has a loss of 0.05 dB or more.

Rotating joints are usually required in a radar system where the transmitter is stationary and the antenna is rotatable. A simple method for rotating part of a waveguide system uses a mode of operation that is symmetrical about the axis, as shown in figures 5-30, views A and B. This requirement is met by using a circular waveguide and a mode

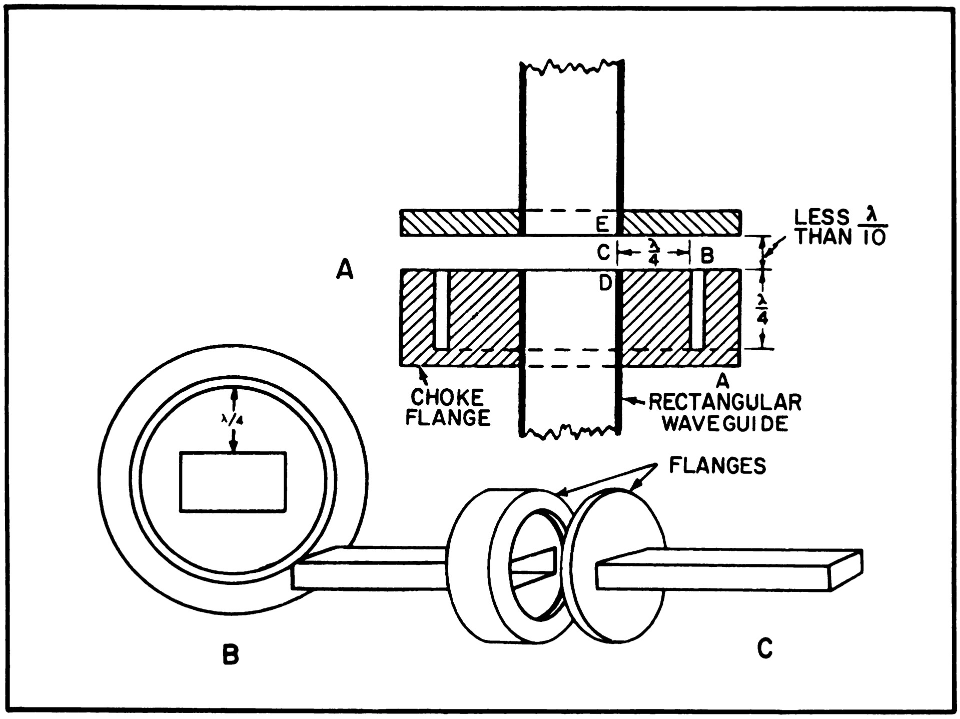

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Figure 5-29.—Choke joint.

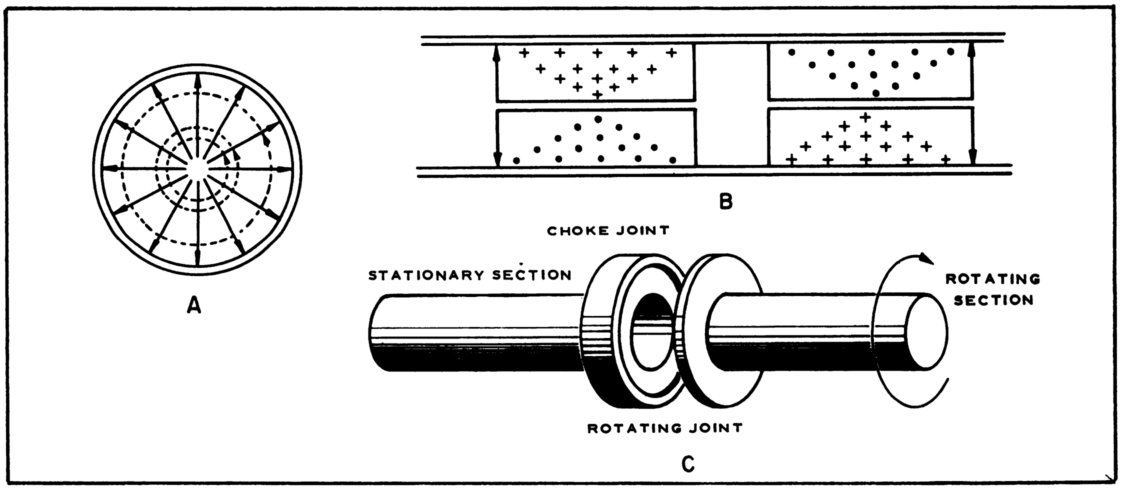

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Figure 5-30.—Basic rotating joint.

such as $TM_{01}$. In this method, a choke joint may be used to separate the sections mechanically and to join them electrically, as shown in figure 5-30, view C. The waveguide rotates, but the field does not. The fixed field minimizes reflections. This is basically the method used for all rotating joints. Since most radars use rectangular waveguides, the circular, rotating joint must be inserted between two rectangular sections. A typical rotating joint is shown in figure 5-31. The joint consists of two sections of circular guide—one stationary and the other rotating. At the ends of each section of circular guide, a transition, from the circular to the rectangular waveguide, occurs.

Note that the rectangular guide is operating in the $TE_{10}$ mode (the lines in the illustration of the guide represent the E-lines). The E-lines couple from the rectangular guide into the circular guide and excite the circular guide in the $TM_{01}$ mode. This is the mode that provides the required axial symmetry for rotating joints. At the top of the joint, the E-lines couple the energy into the rectangular guide, which leads to the antenna. Here the guide is operating in the $TE_{10}$ mode.

## IMPEDANCE CHANGING DEVICES

Often, rf transmission systems are not perfectly matched by their load devices. The standing waves that result are undesirable because of the associated power loss, reduction of power handling capability, and increase in frequency sensitivity. Therefore, impedance changing devices are introduced near the sources of reflected waves.

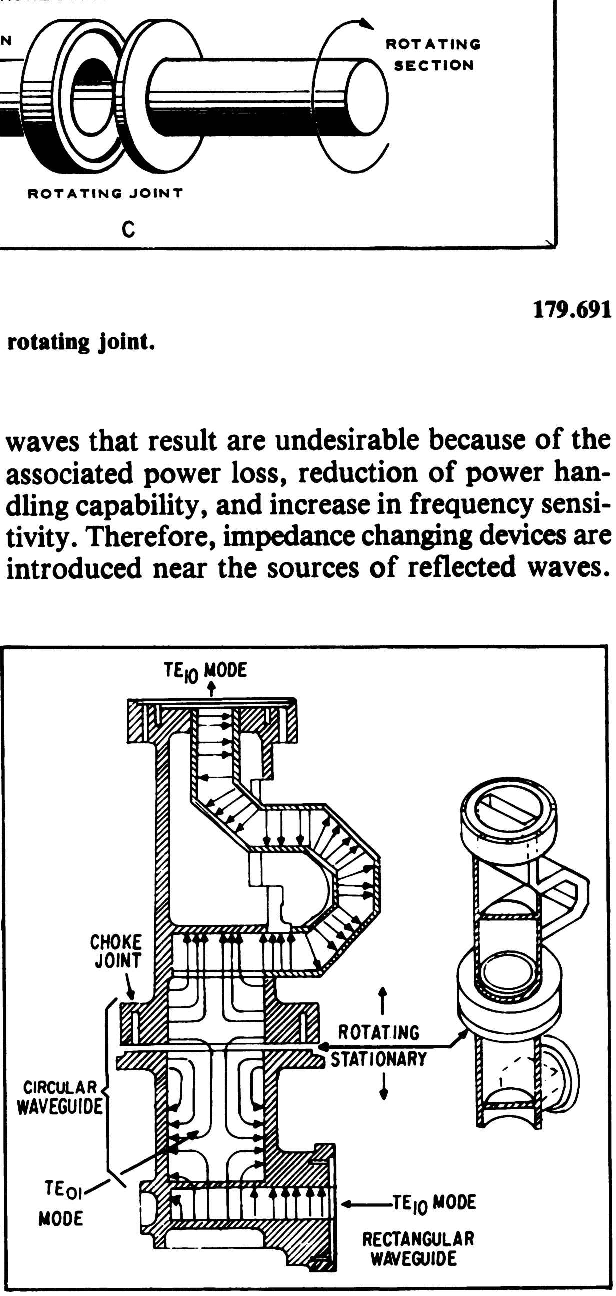

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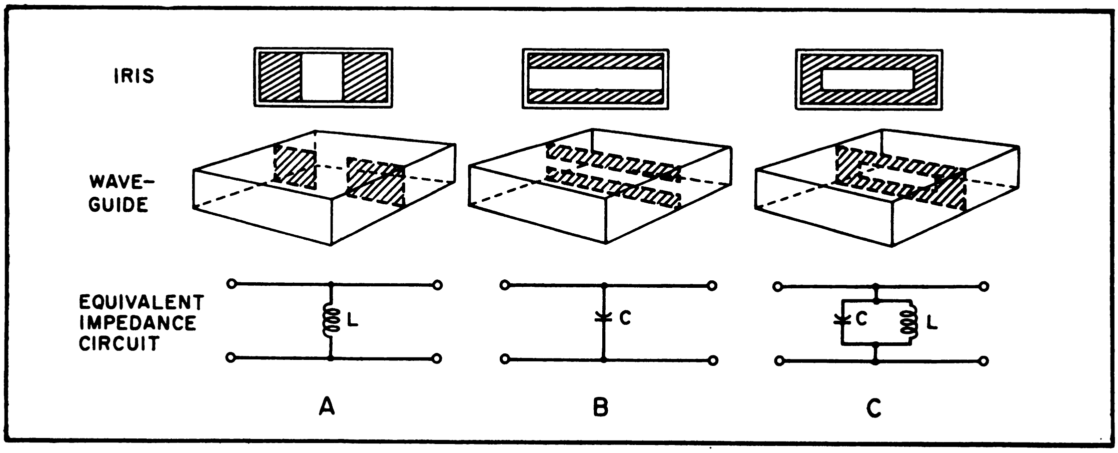
Figure 5-31.—Representative rotating joint.



55.103(179)

Figure 5-32.—Waveguide irises.

These devices provide a standing wave ratio (SWR) nearly equal to unity. Impedance changing devices are also employed near the source to provide a load impedance of optimum value of the source.

The principles used to achieve impedance matching in waveguides are the same as those used in conventional circuits. However, the physical appearance of the matching elements is different.

Figure 5-32 shows three irises used to introduce inductance and/or capacitance into a waveguide, their placement in the waveguide, and their equivalent impedance circuits. An *iris* is a metal diaphragm located in a transverse plane of a waveguide. It contains openings (called windows or apertures) through which the waves may pass.

Figure 5-32, view A, shows an *inductive iris*. It places a shunt inductive reactance across the line. The wider the opening, the higher the reactance. A *capacitive iris* (fig. 5-32, view B) places a shunt capacitive reactance across the line. Again, the wider the opening, the higher the reactance. The iris shown in figure 5-32, view C, forms an equivalent parallel LC circuit across the line. At resonance, the iris places a high shunt resistance across the guide. Above or below resonance, the iris acts as a capacitive or inductive reactance.

Figure 5-33 shows posts and screws used for impedance changing. Conducting posts or screws that penetrate only part way into the guide (fig. 5-33, view A) form shunt capacitive reactances.

When the conducting post or screw extends completely through the guide, making contact with the top and bottom walls, it acts as an inductive reactance (fig. 5-33, view B). The post is not a perfect short circuit because it is encircled by magnetic fields and possesses an inductive reactance. The difference in screws and posts is that the screws can be adjusted to vary the reactance.

## TERMINATING A WAVEGUIDE

Since a waveguide is a single conductor, it is not easy to define its characteristic impedance ($Z_0$). Nevertheless, you may think of the characteristic impedance of a waveguide as being

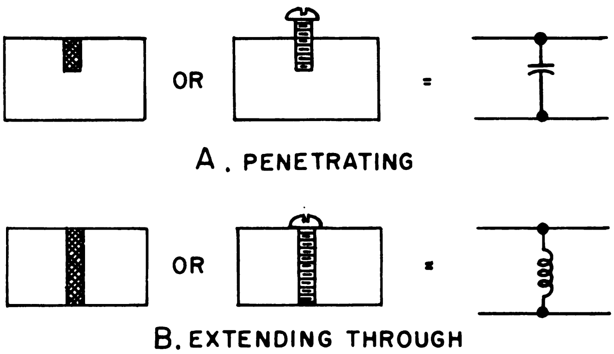


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Figure 5-33.—Conducting posts and screws.

approximately equal to the ratio of the strength of the electric field to the strength of the magnetic field for energy traveling in one direction. This ratio is equivalent to the voltage-to-current ratio in coaxial lines on which there are no standing waves.

On a waveguide, there is no place to connect a fixed resistor with which to terminate the guide in its characteristic impedance. However, there are a number of special arrangements that accomplish the same thing. One arrangement consists of filling the end of the waveguide with a mixture of graphite and sand, as shown in figure 5-34, view A. As the fields enter the sand, they cause current flow through the sand. This current flow creates heat, thereby dissipating energy. None of the energy thus dissipated is reflected back into the guide. Another arrangement (fig. 5-34, view B) uses a high-resistance rod placed at the center of the E-field. The E-field causes current to flow through the rod. The high resistance of the rod dissipates the energy as an $I^2R$ loss.

Still another method for terminating a waveguide is the use of a wedge of high-resistance material (fig. 5-34, view C). The plane of the wedge is placed perpendicular to the magnetic lines of force. When the H-lines cut the wedge, a voltage is induced in it. The current produced by this induced voltage creates an $I^2R$ loss. This loss is dissipated in the form of heat. Therefore, very little energy is permitted to reach the closed end of the guide, thus preventing reflections.

Each of the preceding terminations is designed to match the impedance of the guide to ensure a minimum of reflection. On the other hand, there are many instances where it is desirable for all the energy to be reflected from the end of the guide. The best way to accomplish this is to permanently weld a metal plate at the end of the waveguide, as shown in figure 5-34, view D.

When it is necessary that the end of the guide be removable, a removable plate is attached to the end of the guide. The contact between the guide and the end plate must be exceptionally good. This ensures that current flow will not attenuate the H-field. Perfect contact is not required when the connection is made at a point of minimum current. Such a point is located 1 quarter-wavelength from the end of the guide. When connection is made at this point, a cup is used in place of the end plate (fig. 5-34, view E).

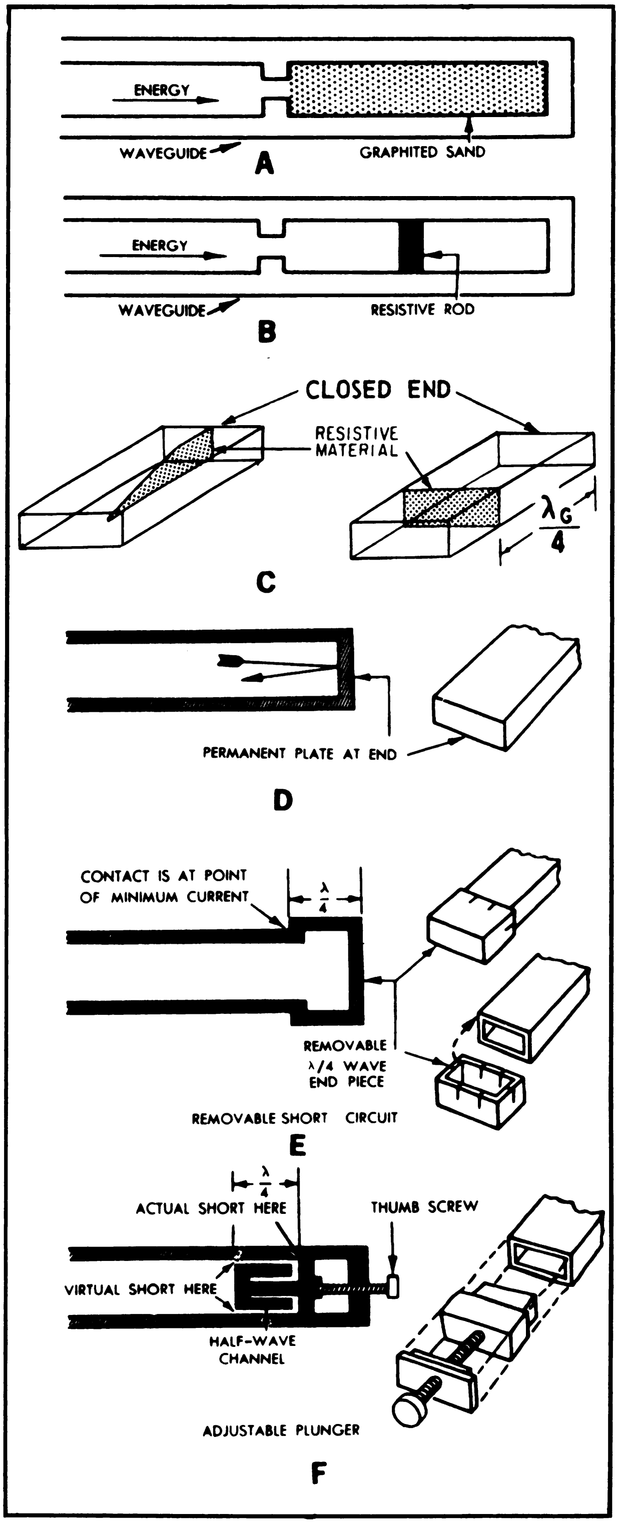

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Figure 5-34.—Terminating waveguides.

This cup is a quarter-wavelength long and large enough to fit over the end of the guide. The voltage across opposite sides of the cup opening is high, but as the reflected H-field cancels the incident H-field, the resulting current is very small and reflection is at a minimum.

When the end of the guide must be adjustable, an arrangement similar to the choke joint, previously explained, is employed. Principally, it consists of an adjustable plunger that fits into the guide, as shown in figure 5-34, view F. The walls of the waveguide and the plunger form a half-wave channel. The half-wave channel is closed at one end and reflects a short circuit across the other end. This results in a perfect connection between the wall and the plunger. The actual physical contact is made at a quarter-wavelength from the short circuit, where the current is minimum due to the standing waves. This makes it possible for the plunger to slide loosely in the guide at a point where the contact resistance to current flow is very low.

## CAVITY RESONATORS

Circuits composed of lumped inductance and capacitance elements may be made to resonate at any frequency from less than 1 hertz to many thousand megahertz. At extremely high frequencies, however, the physical size of the inductors and capacitors becomes extremely small. Also, losses in the circuit become extremely great. Therefore, resonant devices of different construction are preferred at extremely high frequencies. In the UHF range, sections of parallel wire or coaxial transmission lines are commonly employed in place of lumped, constant resonant circuits. In the microwave region, cavity resonators are used. Cavity resonators are metal-walled chambers fitted with devices for admitting and extracting electromagnetic energy. The Q of these devices may be much greater than that of conventional LC tank circuits.

Although cavity resonators are built for different frequency ranges and applications and have a variety of physical forms, the basic principles of operation are essentially the same for all. Resonant cavity walls are made of highly conductive material and enclose a good dielectric, usually air. One example of a cavity resonator is the rectangular box, shown in figure 5-35, view A. It may be thought of as a section of rectangular waveguide closed at both ends. Because the end plates are short circuits for waves traveling in the Z direction, the cavity is analogous to a transmission line section with short circuits at both ends. Resonant modes occur at frequencies for which the distance between end plates is a half-wavelength or multiple of a half-wavelength.

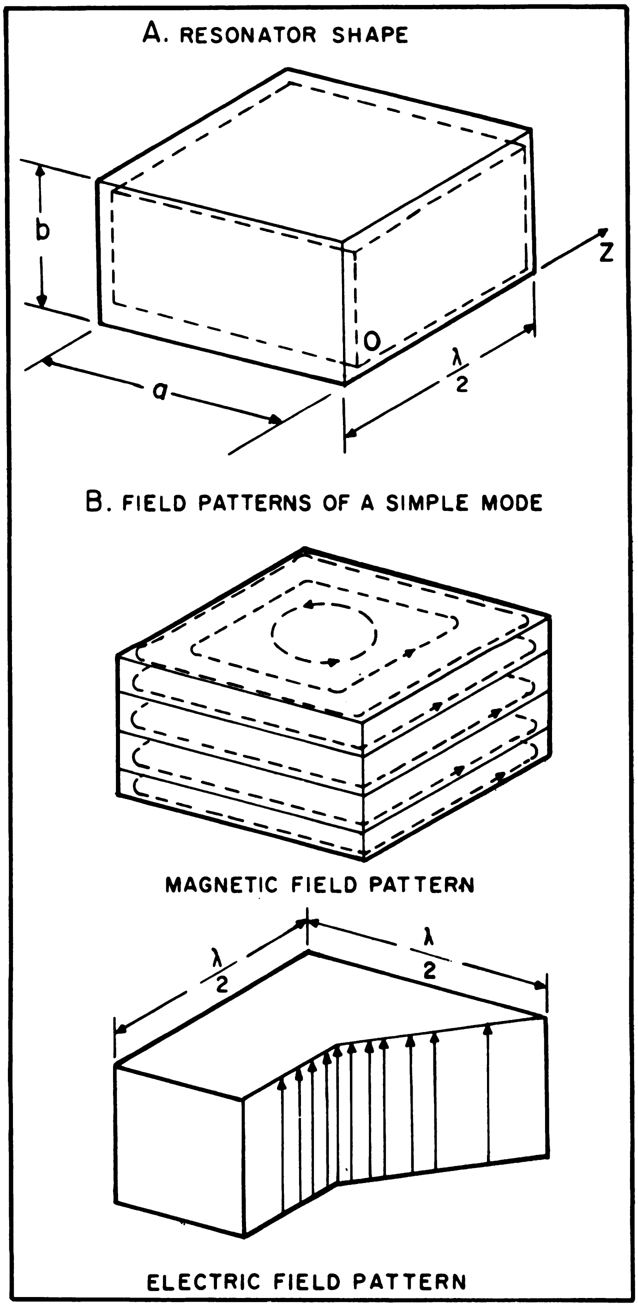

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Figure 5-35.—Rectangular-waveguide resonator.

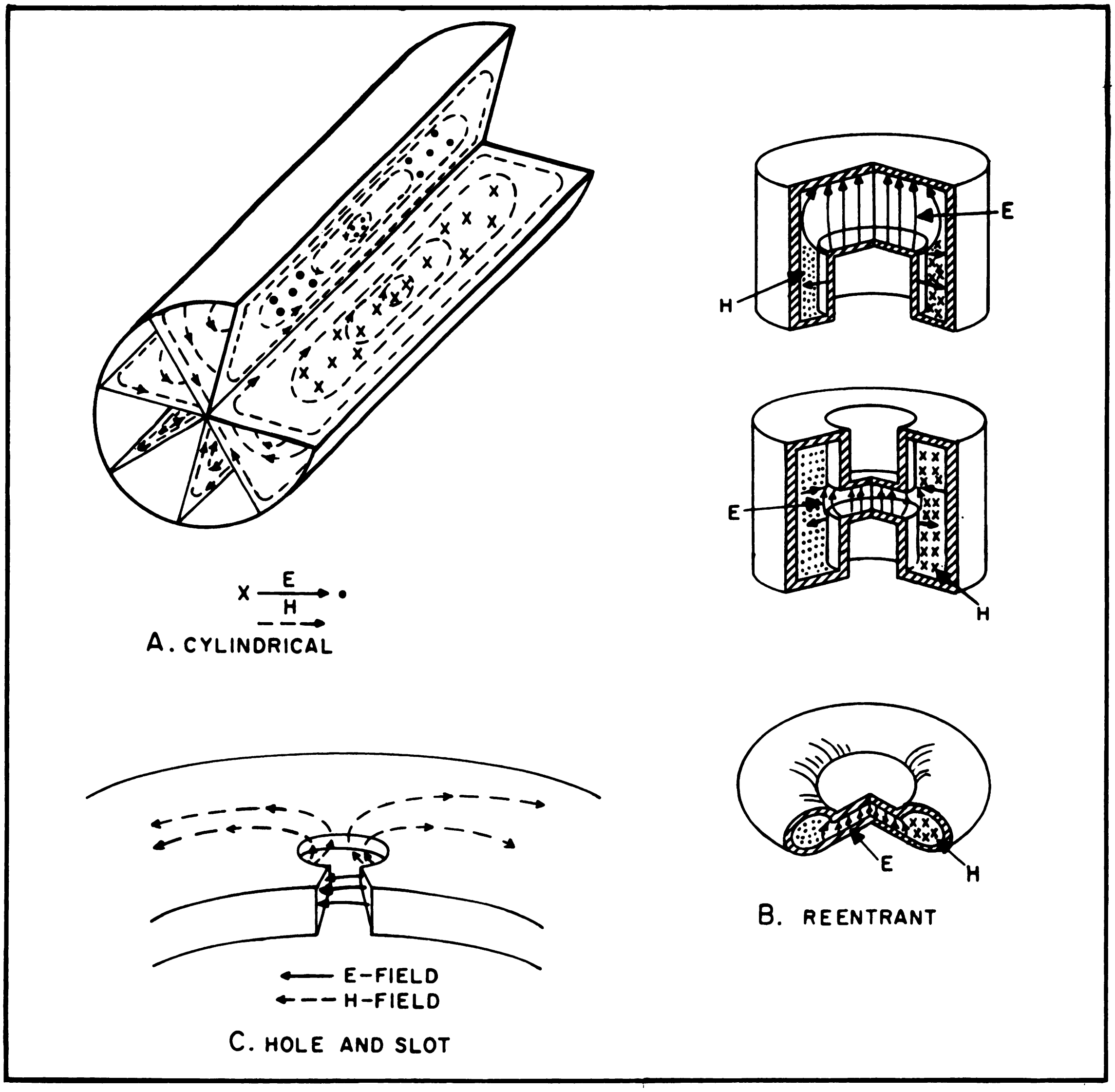

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Figure 5-36.—Types of cavities.

Cavity modes are designated by the same numbering system that is used with waveguides, except that a third subscript is used to indicate the number of half-wave patterns of the transverse field along the axis of the cavity (perpendicular to the transverse field). For example, the mode shown in figure 5-35, view B, is $TE_{101}$. This field configuration is obtained by the addition of the fields of the component traveling waves. Observe that the pattern is similar to one segment of the pattern of the $TE_{10}$ mode of a wave-guide. The only difference is that the loops formed by the magnetic field lines are shifted 1 quarter-wavelength with respect to the electric field lines. This shift is the result of adding the two oppositely directed traveling waves.

The rectangular cavity is only one of many cavity devices useful as high-frequency resonators. By appropriate choice of cavity shape, advantages such as compactness, ease of tuning, simple mode spectrum, and high Q may be secured as required for special applications.

Figure 5-36 shows some other cavity types and possible field configurations. View A is a cylindrical cavity. Several examples of a type of cavity known as a reentrant cavity are shown in view B. View C depicts a hole and slot type of cavity commonly used in magnetron oscillators.

## CAVITY TUNING

The resonant frequency of a cavity may be varied by changing any of three parameters: *cavity volume, cavity inductance*, or *cavity capacitance*. Although the mechanical methods for tuning cavity resonators may vary, they all use the electrical principles explained below.

Figure 5-37 shows a method of tuning a cylindrical type of cavity by varying its volume. Varying the distance D results in a new resonant frequency. Increasing distance D lowers the resonant frequency, while decreasing D causes an increase in resonant frequency. The movement of the disk may be calibrated in terms of frequency. A micrometer scale is usually used to indicate the position of the disk, and a calibration chart is used to determine frequency.

A second method for tuning a cavity resonator is shown in figure 5-38, view A. Here, a nonferrous, metallic screw is inserted into a cavity at a point of maximum H-field. This decreases the permeability of the cavity and decreases its effective inductance, which raises its resonant frequency. The farther the screw penetrates into the cavity, the higher the resonant frequency becomes. A paddle (fig. 5-38, view B) can be used in place of the screw. Turning the paddle to a position more nearly perpendicular to the H-field increases the resonant frequency.

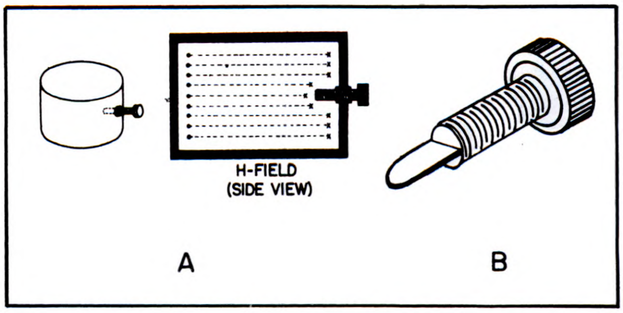

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Figure 5-38.—Cavity tuning by inductance.

Tuning a reentrant cavity by varying its capacitance is shown in figure 5-39. The E-field in this type of cavity may be assumed to be uniform and contained wholly within the gap between center plates. Adjusting the screw expands or contracts the lever that varies the distance between the center plates. Varying the

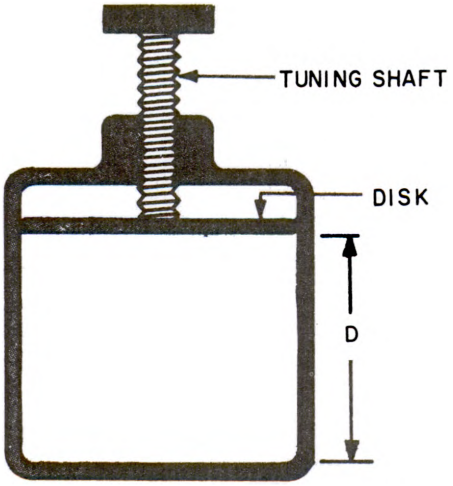

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Figure 5-37.—Cavity tuning by volume.

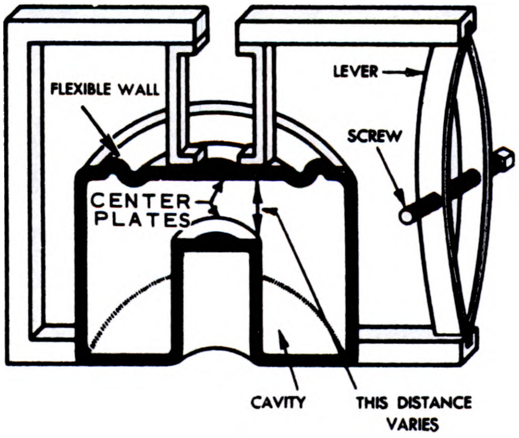

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Figure 5-39.—Cavity tuning by capacitance.

distance between these center plates varies the effective cavity capacitance, which, in turn, varies the cavity resonant frequency. Increasing this distance decreases capacitance, and therby increases the resonant frequency. The wall of this type of cavity has to be flexible to allow the movement necessary for tuning.

## CAVITY COUPLING

As with conventional LC tank circuits, a method of introducing and removing energy is required. There are three principal methods of accomplishing this: *probe coupling, loop coupling*, and *aperture* or *slot coupling.*

Figure 5-40, view A, illustrates probe coupling. The probe is inserted into the cavity at a point of maximum E-field and sets up E-lines, thus starting and maintaining oscillation. This is a form of capacitive coupling. View B illustrates loop coupling. Here, a loop is placed in the cavity at a point of maximum H-field, where it introduces an H-field into the cavity. This is a form of inductive coupling. Energy may be introduced or removed through an aperture or slot cut in a wall that is common to the guide and resonator. This is illustrated in view C of figure 5-40. Coupling results from the penetration of electromagnetic fields through the opening.

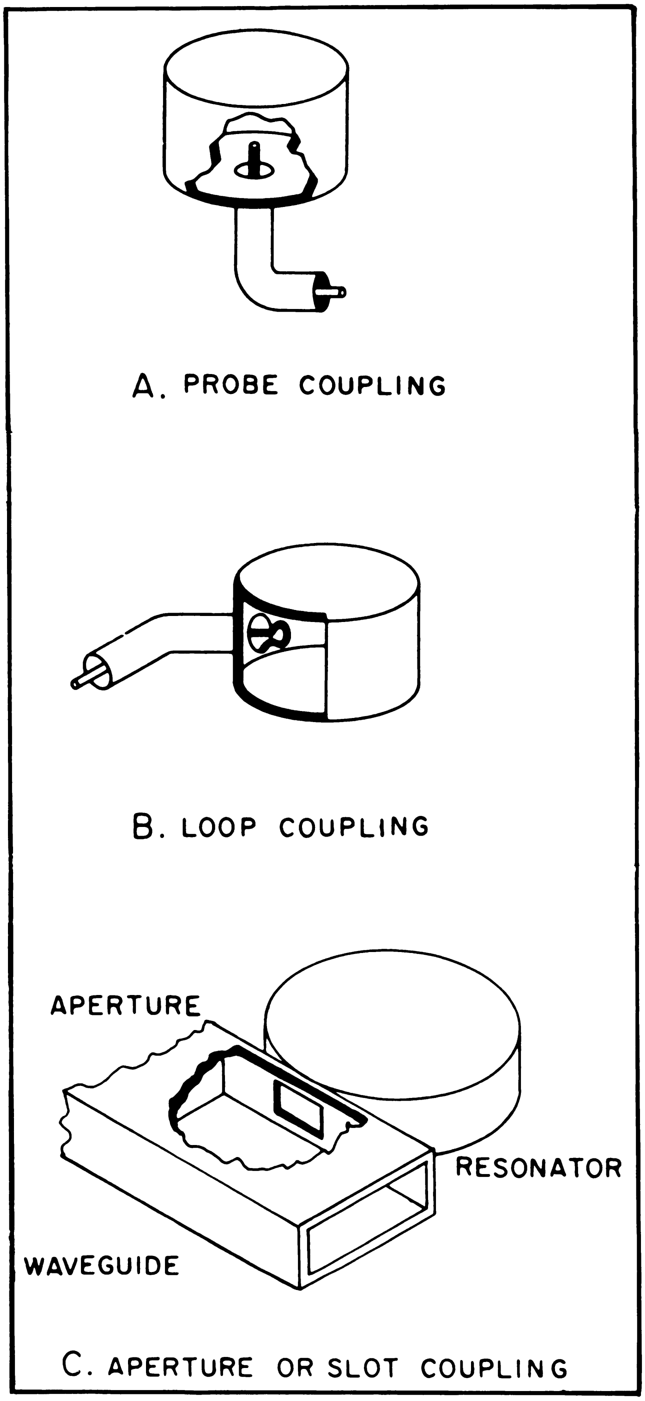

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Figure 5-40.—Cavity coupling.

## HYBRID JUNCTIONS

Hybrid junctions are used in waveguide applications as balanced mixers, balanced duplexers, and as switches and power splitters. Two common types of hybrid junctions are the *magic T* and the *hybrid ring* or *rat race.* Another more recent development is the *short-slot hybrid junction.* The magic T and the hybrid ring are discussed in detail after a simplified explanation of the action of E-type T junctions and H-type T junctions.

## T JUNCTIONS

E TYPE. An E-type T junction is shown in figure 5-41, view A. The name derives from the fact that the arm (labeled b) extends from the guide in the line of direction of the E-field and the a and c arms (fig. 5-41, view B). The reversal of the arrows in arm a with respect to those in arm c indicates a phase reversal of the electric field of 180°. Although they are not shown in the figure, electromagnetic lines always accompany the electrostatic lines. For simplicity, the electromagnetic lines have been omitted.

In figure 5-41, view B (1), the signal is fed into arm b, and out-of-phase signals are obtained from arms a and c. In view B (2), in-phase signals with equal amplitude are fed into arms a and c, and no output signal is obtained from arm b. In view B (3), out-of-phase signals are fed into arms a and c, and an output is obtained from arm b. In view B (4), there is one input and two outputs; the same is true of view B (5), except that the signal is fed in a different arm.

H TYPE. An H-type T junction is shown in figure 5-42, view A. The name derives from the fact that arm b extends from the guide with the longitudinal axis of arm b parallel to the planes of the H-lines (magnetic). For simplification, only the E-fields for various inputs are shown in the illustrations of view B. In view B, the junction is tilted so that arm b points down. The plus signs indicate that the direction of the E-lines is away from the observer. The dots indicate the direction of the E-lines is toward the observer. A phase shift of 180° occurs as the directions reverse. The lines are crowded in the center of the guide (for the $TE_{10}$ mode) where the field is strongest and less crowded away for the center where the field is weaker. At the boundary surfaces paralleling the E-lines, the E-field is zero.

In figure 5-42, view B (1), the signal is fed into arm b, and equal in-phase signals are obtained from arms a and c. In view B (2), equal in-phase signals are fed into arms a and c, and then an output signal is obtained from arm b. If equal out-of-phase signals are fed into arms a and c, as in view B (3), no output is obtained

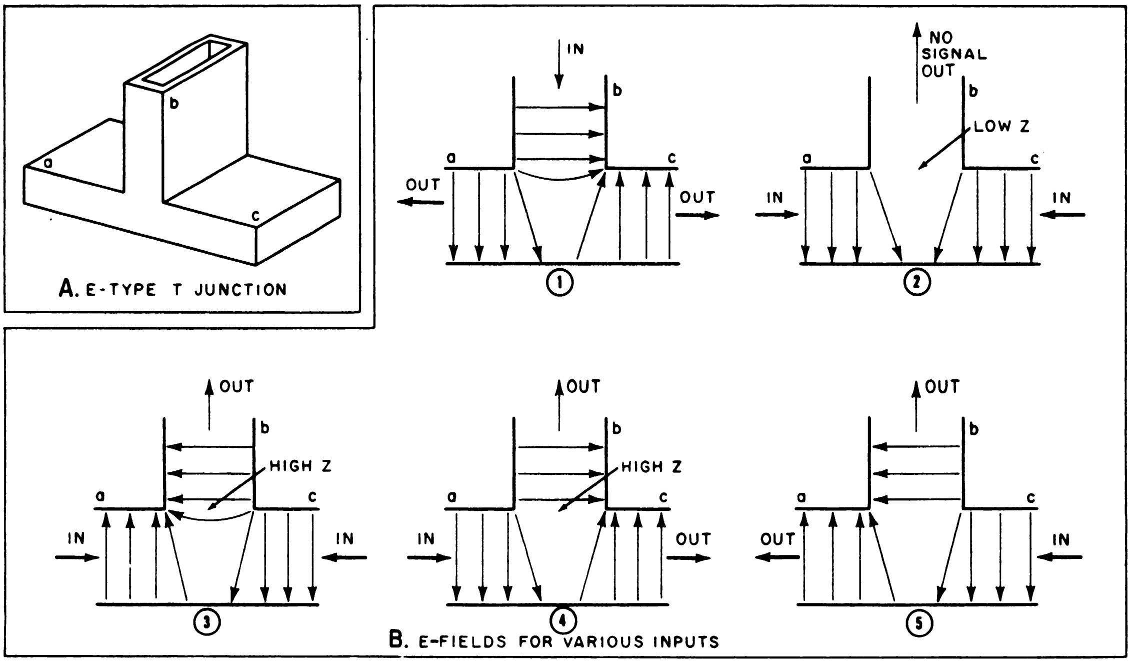

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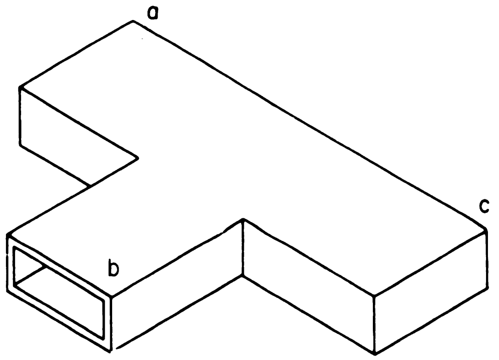
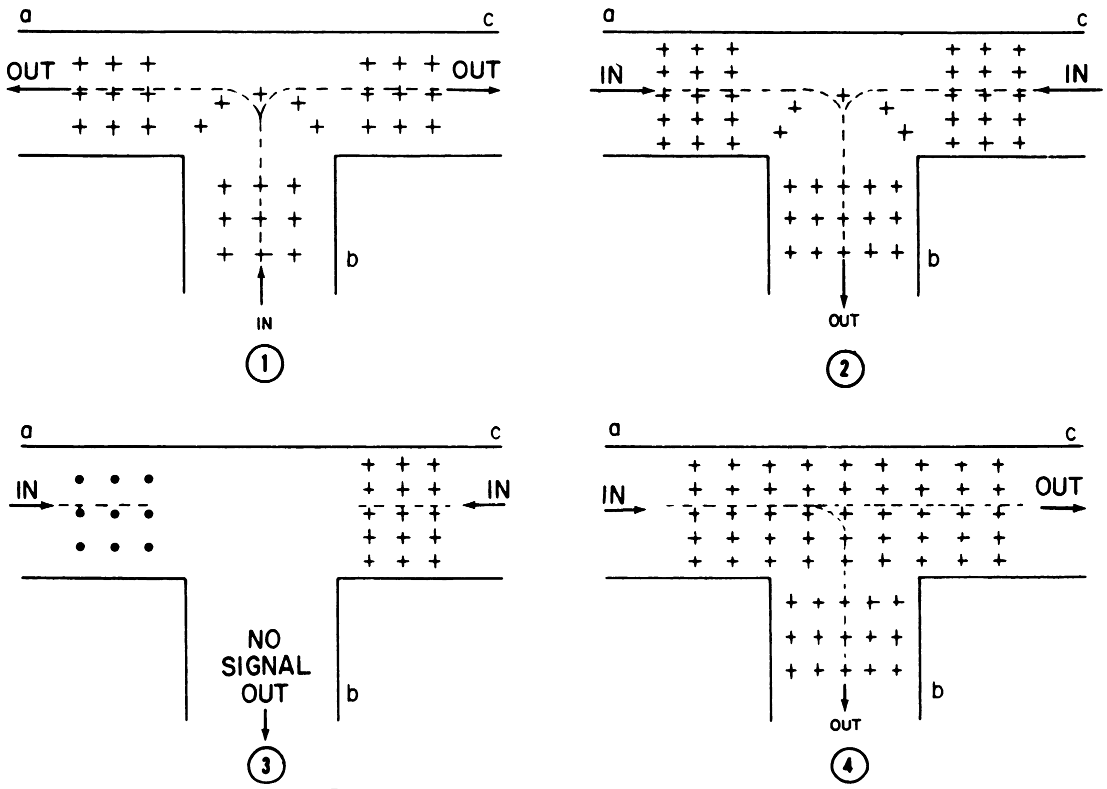
Figure 5-41.—E-type T junction and E fields.



A. H-TYPE T JUNCTION



B. FIELDS FOR VARIOUS INPUTS

25.181

Figure 5-42.—H-type T junction and E fields.

from arm b. If, as in view B (4), a signal is fed into arm a, an output will be obtained from arms b and c. Similarly, if a signal is fed into arm c, an output will be obtained from arms a and b (not shown).

## THE MAGIC T

A simplified version of the magic T, shown in figure 5-43, is used as a balanced mixer at the input of radar receivers. The echo pulses from the antenna are relatively weak, and noises generated in the local oscillator are balanced out by the action of the magic T. Without this action, the noises would be of sufficient amplitude to interfere seriously with the signal.

The operation of the magic T may be explained briefly as follows:

1. The output of the klystron local oscillator is fed into the H-plane arm. As indicated in figure 5-42, view B (1), the oscillator signal will divide into two in-phase components, one going into arm a and one going into arm c.

2. The relatively weak echo signal from the antenna is fed into the E-plane arm. As indicated in figure 5-41, view B (1), this signal will divide into two out-of-phase components that will move into arms a and c.

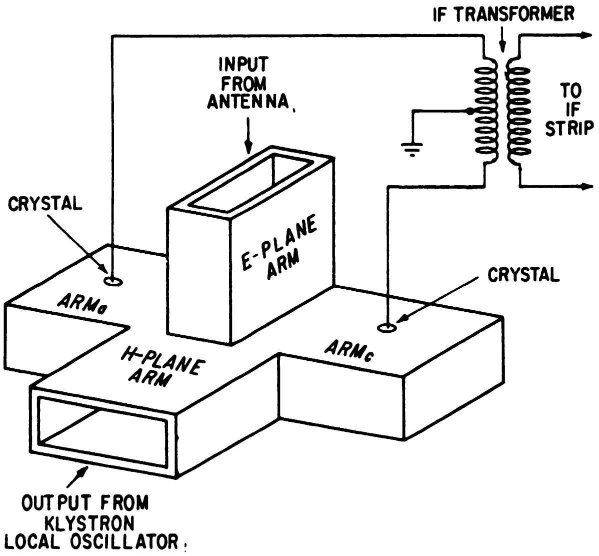


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Figure 5-43.—Balanced mixer employing a magic T.

3. The signal entering the E-plane arm will not enter the H-plane arm because of the zero potential (satisfying the boundary condition of zero potential at the side of the E-plane arm) existing at the entrance to the H-plane arms. Maximum potential should exist at the entrance if energy is to move down this arm.

4. The signal entering the H-plane arm will not enter the E-plane arm because there is no potential difference across the input of the E-plane arm.

5. From the H-plane arm, in-phase oscillator signals of relatively large amplitude are coupled to the crystal rectifiers, which are correctly positioned in the guide to couple out the energy.

6. However, the rectified in-phase signals from the local oscillator are balanced out in the primary of the IF transformer and do not appear at the output. From the E-plane arm, out-of-phase signals of relatively small amplitude (echo signals) are also coupled to the crystal rectifiers. The rectified echo signal, although properly phased to produce a balanced input to the IF transformer, will not produce an appreciable output at the secondary because of the low energy contained in the signal and the capacitive shunting effect to ground.

7. The crystal rectifiers are nonlinear devices, and the output from each crystal is an IF signal equal to the difference between the local-oscillator frequency and the incoming signal frequency. Because of the out-of-phase signals fed from the E-plane arm to the two crystals, the IF amplitude variations at the outputs of the crystals will be 180° out of phase with each other. This action produces a balanced input at the difference frequency to the transformer.

8. Noise generated in the local oscillator will reach the primary of the IF transformer in phase. Thus, it will be cancelled out.

In applications (for example, in mixing circuits) where small amounts of power are involved, the magic T may be used to advantage. However, unless some type of matching device is used, power losses will result. When matching devices are used, the power handling capability is reduced. Therefore, the magic T is normally not used as a duplexer in high-power radar systems.

## THE HYBRID RING

The hybrid ring is used principally as a duplexer in a high-power radar system. However, a combination of three hybrid rings may be used as a balanced mixer. This type of mixer is very effective in isolating the receiver from the transmitter during the time the transmitter is firing.

A simplified version of the hybrid ring used as a duplexer is illustrated in figure 5-44, views A and B. The operation during transmission and reception is illustrated in views C and D, respectively.

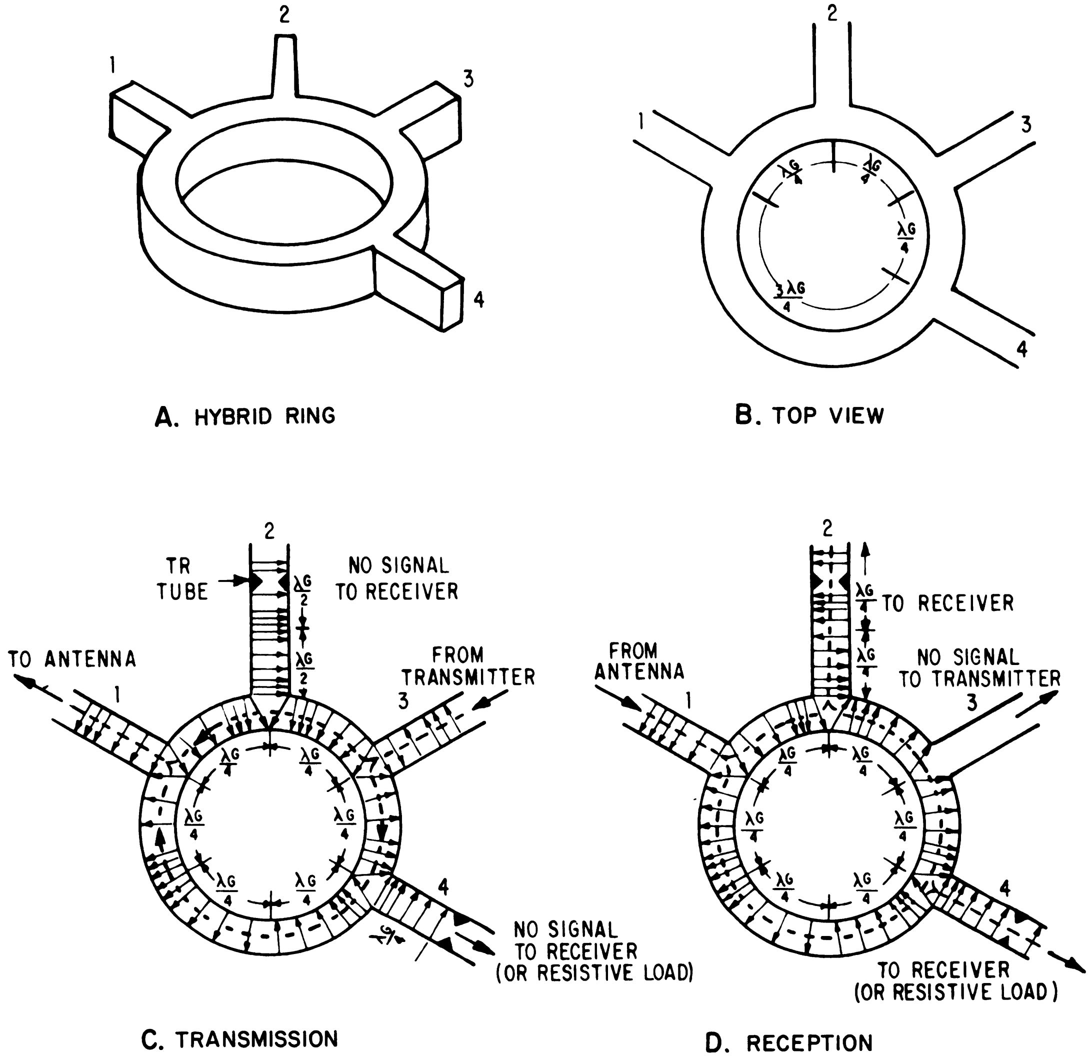

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Figure 5-44.—Hybrid ring duplexer showing E lines during transmission and reception.

During *transmission* (fig. 5-44, view C), the operation of the hybrid ring may be explained as follows:

1. The field from the transmitter enters arm 3. At the junction with the ring, the field divides into two out-of-phase fields, one moving clockwise around the ring and the other counterclockwise as previously shown in figure 5-41, view B (1). For energy to be coupled to the antenna through arm 1, the E-fields arriving at the arm 1 junction must be 180° out of phase as previously shown in figure 4-41, view B (3).

2. The field moving clockwise around the ring from arm 3 fires the TR (transmit-receive) tube in arm 4, and the energy is blocked from the receiver or load. A high impedance (equivalent to an open circuit) appears at the junction of arm 4 and the ring. There is a phase reversal at this junction as previously shown in figure 5-41, view B (4).

3. The field moving counterclockwise from arm 3 *sees* a short circuit at the arm 2 junction when the TR tube in arm 2 fires, and there is no phase reversal at this junction. The amount of energy entering waveguide 2 is limited by the action of the spark gap.

4. If the complete circuits are traced out, it will be seen that the clockwise and counterclockwise signals arriving at the junction of arm 1 are of opposite polarity and will be propagated through the arm to the antenna as previously shown in figure 5-41, view B (3).

During *reception* (fig. 5-44, view D), the operation of the hybrid ring may be explained as follows:

1. The relatively weak signal from the antenna enters arm 1 and divides at the junction into two out-of-phase components as previously shown in figure 5-41, view B (1). To avoid coupling energy into the transmitter by way of arm 3, in-phase signals must arrive from both directions at this junction as previously shown in figure 5-41, view B (2).

2. The energy moving clockwise around the ring from arm 1 is not sufficient to fire the TR tube in arm 2, and energy passes to the receiver through arm 2. There is a phase reversal (guide 2 presents high Z at the junction with the ring, as previously shown in figure 5-41, view B (4), and the remainder of the energy moves clockwise around the ring to arm 3.

3. The energy moving counterclockwise around the ring from arm 1 is not sufficient to fire the TR tube in arm 4, and energy passes to the receiver through arm 4. There is a phase reversal, as previously shown in figure 5-41, view B (4), and the remainder of the energy moves counterclockwise around the ring to arm 3.

4. At arm 3, the clockwise and counterclockwise components are in phase, and no energy is coupled to the transmitter through arm 3 as previously shown in figure 5-41, view B (2).

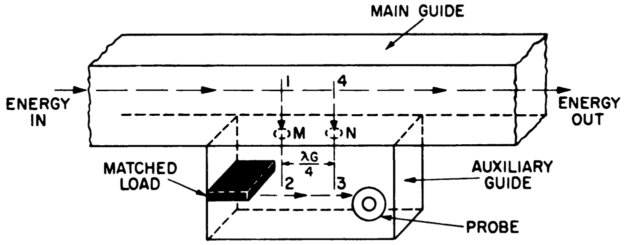
## DIRECTIONAL COUPLERS

Directional couplers are used in microwave systems to monitor power that moves in one particular direction along a transmission line (for example, a coaxial line or a waveguide). The power extracted is only a small portion of the power propagated along the transmission line; however, its magnitude must be proportional to the magnitude of the power propagated along the line. The coupling units are arranged so that reflected signal power does not affect the accuracy of the measurements.

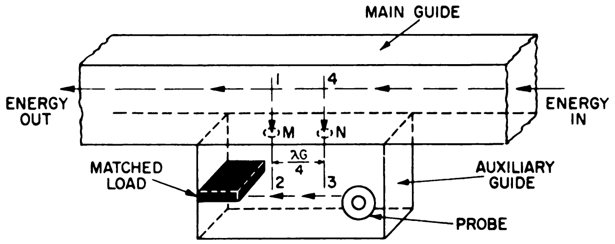
Directional couplers are an integral part of radar systems and are so connected in the transmission line that either the transmitted or the reflected power may be sampled. One-way directional couplers are discussed first, and then bidirectional couplers are described.

### TWO-HOLE DIRECTIONAL COUPLER

A simplified version of a two-hole directional coupler is shown in figure 5-45. A small percentage of the energy flow from left to right is coupled to the probe. However, energy flow from right to left is not coupled to the probe,



A. POWER FLOW FROM LEFT TO RIGHT



B. POWER FLOW FROM RIGHT TO LEFT

1.264

Figure 5-45.—Two-hole directional coupler.

but is dissipated in the matched load. The action of the coupler may be explained by the use of the figure.

In figure 5-45, view A, energy is coupled from the primary guide to the secondary guide by the two small holes. Energy that moves to the probe through path 1-2-3 traverses the same distance as the energy that moves to the probe through path 1-4-3. Therefore, these two energy components arrive at the probe in phase and may be coupled out to the measuring device.

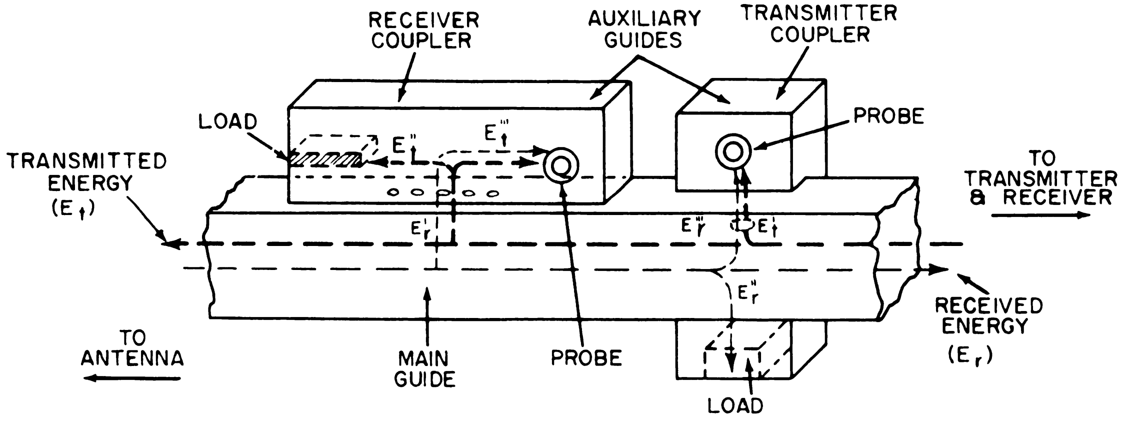
Energy arriving at the matched load through path 1-4-3-2 travels a half-wavelength farther than the energy arriving at the matched load through path 1-2. These two energy components arrive out of phase and, therefore, cancel.

In figure 5-45, view B, energy moves from right to left. That part of the energy moving through path 4-3-2 passes through the same distance as the part moving through path 4-1-2. Therefore, these two energy components arrive in phase at the matched load where they are absorbed.

Energy arriving at the probe through path 4-1-2-3 travels a half-wavelength farther than the energy arriving at the probe through path 4-3. Therefore, these two energy components arrive at the probe out of phase and cancel.

## BIDIRECTIONAL COUPLER

A simplified diagram of a bidirectional coupler used in a radar system is shown in figure 5-46. Energy from the transmitter is fed in at the right-hand end of the main guide, and the echo energy from the target is fed in at the left-hand end of the guide. Some of the transmitted energy is coupled through the coupling holes (between



67.33

Figure 5-46.—Bidirectional coupler.

the main guide and the coupler) into the transmitter coupler auxiliary guide. This portion of $E_t$, labeled $E_t'$, is about $-40$ dB $(\frac{1}{10,000})$ of the transmitted energy. It may be coupled out at the transmitter coupler probe. Another portion of the transmitted energy (labeled $E_t''$ ) about $-25$ dB $(\frac{1}{315}\ E_t')$ enters the receiver coupler. This energy is dissipated in the load. In addition, a very small amount of $E_t$ (approximately $-60$ dB $(\frac{1}{1,000,000})$ of $E_t$ and labeled $E_t'''$ ) couples to the receiver coupler probe.

Some of the echo, or received, energy ($E_r$), labeled $E_r'$, is coupled to the probe in the receiver coupler. This energy is about $-25$ dB of $E_r$. A second portion of $E_r$ (labeled $E''$, and about $-$ 40 dB of $E''$) is coupled to the load in the transmitter coupler. A third portion of $E_r$ (labeled $E_r'''$, and about $-30$ dB of $E_r$) is coupled to the probe in the transmitter coupler.

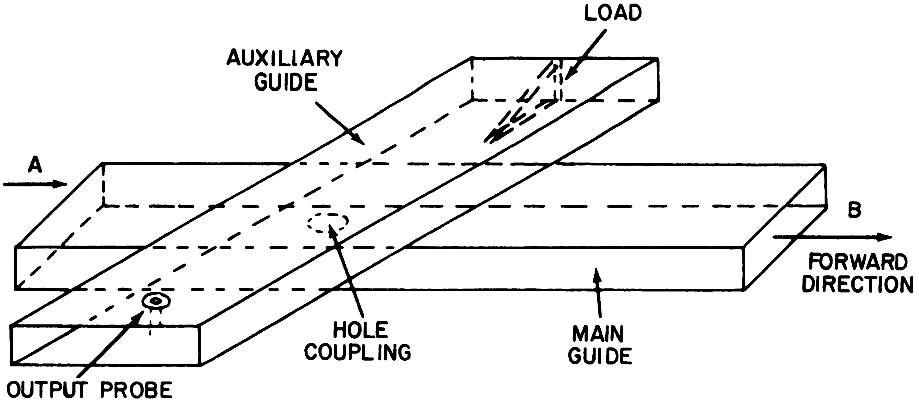
Both the transmit coupler and the receive coupler may be considered to have a certain *coupling factor* and a certain *directivity*.

The coupling factor determines the proportion of the energy existing in the main guide, which is coupled into the auxiliary guide. The orientation of the coupling holes determines whether a particular wave will be coupled to the probe or to the load end of the couplers. Figure 5-46 shows that energy traveling from right to left in the main guide couples to the probe in the transmitter coupler and to the load in the receiver coupler. It also shows that for a wave traveling from left to right, the received energy couples to the probe in the receiver coupler and to the load in the transmitter coupler.

The directivity of the coupler is a measure of the amount of the unwanted wave that reaches the output probe. The symbols $E_t'''$ and $E_r''$ represent unwanted energies in the respective couplers.

## BETHE-HOLE COUPLER

A Bethe-hole coupler is shown in figure 5-47. Waves are excited in the auxiliary guide by both the electric and the magnetic field in the main guide. Because of the phase relations involved in coupling the energy through the hole, the waves cancel in the forward direction and reinforce in the reverse direction. That is, energy entering at A is coupled to the probe, but energy entering at B is absorbed in the load. If the two guides were parallel, there would be a greater degree of coupling of the magnetic component than of the electric component, and the directivity would be poor. By placing the auxiliary guide at the proper angle, the magnetic and electric components that are coupled into the auxiliary guide may be made equal and the desired directivity thus obtained.



67.35

Figure 5-47.—Bethe-hole directional coupler.

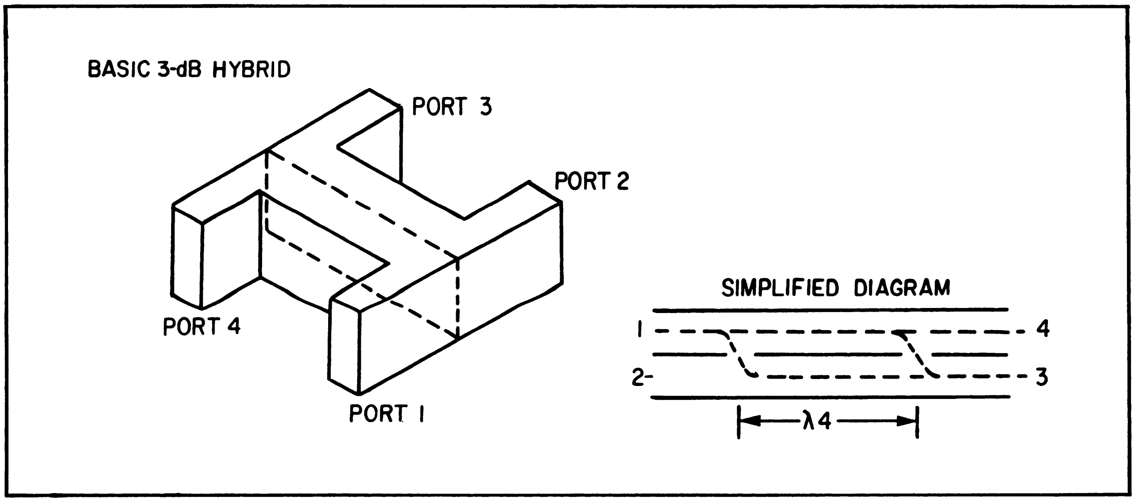
## 3-DB HYBRID

Shown in figure 5-48 is a 3-dB hybrid. It can be considered as two separate waveguides coupled to each other through slots cut into a common wall. The simplified illustration shows two openings in the common wall. These openings are spaced 1 quarter-wave apart and large enough to allow a half-power split in the hybrid. A signal into port 1 will go toward port 4. As it passes the openings, some of the signal will go through and on to port 3. When it goes through the openings, it will receive a +90° phase shift. The result is a signal at port 3 equal to but 90° out of phase with the output at 4. The signal is prevented from going to port 2 because of the quarter-wave spacing of the openings. Energy through the first opening toward port 2 is cancelled by an equal amount going 1 quarter-wavelength further to the second opening, through it and back, arriving 180° out of phase. An input at port 2 will behave similiarly to a port 1 input.

Equal inputs into ports 1 and 2 can be entirely diverted to port 3 or 4 by adjusting their phase difference to 90°. Let input 1 lead 2 by 90°. Then, energy from 2 will be advanced by 90° as it goes through the openings, and, thus, it will be in phase with the input 1 energy and go on to port 4. Energy from port 1 will be advanced an additional 90° as it passes through the openings, thus cancelling any energy flow to port 3. By reversing the input phase difference, all of the energy will go to port 3.

## FERRITES

Before ferrites were used at microwave frequencies, the rf energy in a radar was manipulated by varying the characteristics and dimensions of the rf system. The important point is that the system was made to conform to the microwave frequency and not the microwave to the system. The rf system was tuned to a given frequency by adjusting values that were determined by that frequency. But the frequency stability of a microwave rf generator, a magnetron for example, is dependent upon the impedance into which it works. In a radar, a relatively large and time varying mismatch (as in the case of a scanning antenna fed by flexible joints) may be connected to the magnetron. A mismatch often causes excessive frequency pull on the magnetron, throwing the transmitter out of tune. Ferrites have unique magnetic properties that provide a variable reactance, which makes it possible to adjust or manipulate the microwave energy to conform to the transmission system and to electrically vary the characteristic impedance of the radar's rf



55.434

Figure 5-48.—3dB Hybrid.

system. Ferrites are used as load isolators, phase shifters, variable attenuators, modulators, and switches.

## FUNDAMENTALS OF FERROMAGNETISM

The theory of ferromagnetism is a continuation of the conventional theory of magnetism. To understand ferrites, the nature of the magnetic domain must be known. An individual domain obtains its overall magnetic properties from the perpetually moving electrons within its atomic structure.

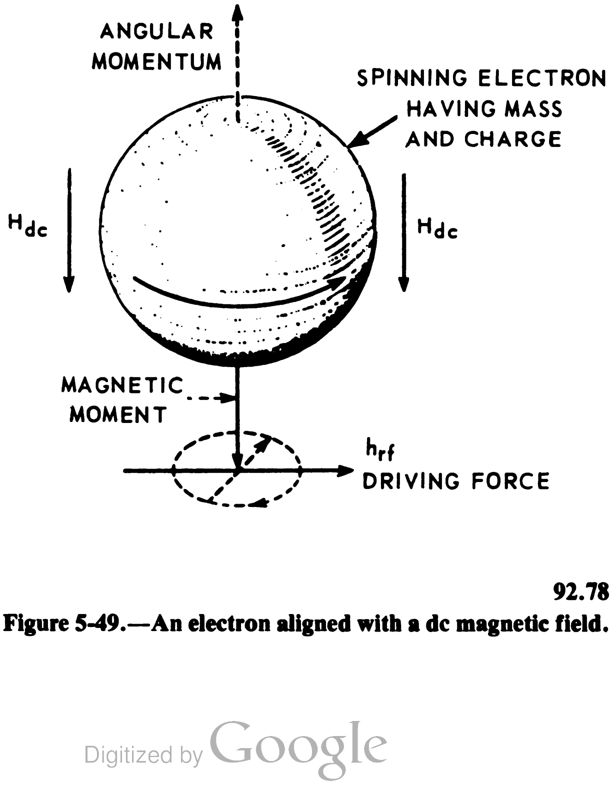
### Electron Motion

An electron has two angular motions within its atom. The orbital motion of the electron about the nucleus is well known. A less familiar motion is the electron's spin about its own axis. The electron's motions are comparable to the Earth's orbital motion about the Sun and its axial rotation.

The electron is a negatively charged particle of matter. Since the electron has an electrical charge, its motion is a current flow within the atom. Because of this current flow, magnetic fields exist perpendicular to the electron's motions. The electron's orbital magnetic fields contribute little to the magnetic properties of the domain. It is the magnetic fields created by the spin motion of the electrons that combine to make up magnetic domains. Atoms of most elements have as many electrons spinning in one direction as the other, so that the magnetic fields of the electrons cancel out. These elements do not have any noticeable magnetic effects. The iron atom, however, has four more electrons spinning in one direction than in the other. The uncanceled magnetic fields of these electrons make the iron atom a permanent magnet. The prefix *ferro* in ferromagnetism means iron. When the uncompensated magnetic fields in adjacent atoms become mutually aligned, the fields add, and a magnetic domain is established. The magnetic domain, also called an elementary magnetic dipole, exhibits appreciable amounts of magnetic force. The individual domains are normally arranged in a random manner within the material, and their magnetic properties cancel. When an external dc field is applied, the spin axes of the electrons in the domains align with the field (fig. 5-49). This is because of the interaction between the electrons' magnetic fields and the external field. As a result, the domains become mutually aligned and their magnetic fields add. If the external field is removed, the magnetic domains tend to remain in mutual alignment.

As a consequence of their spinning motion, electrons behave like small gyroscopes. You know that gyros have the properties of rigidity and precession. Since gravity has little effect on the electron due to its small mass, a steady dc magnetic field can line up the axes of the spinning electrons. The electrons, possessing rigidity of plane of rotation, tend to remain aligned with a point in space that coincides with the applied field's axis.

The theory that an electron has the properties of a gyro is used to explain the behavior of a ferrite. Electron precession in a ferrite is caused by the electron's orbital motion about the nucleus and the force within the material that holds it together. When a static magnetic field is applied, the electrons tend to align their spin axes with the newly applied force. The electron wobbles on its spin axis to establish a state of equilibrium between the internal binding force and the field force. As a result of the two forces, the electron wobbles on its spin axis at a natural



92.78

Figure 5-49.—An electron aligned with a dc magnetic field.

precessional frequency. This frequency varies with the strength of the applied field. The net direction of the spin axis of the electron remains aligned with the field's axis.

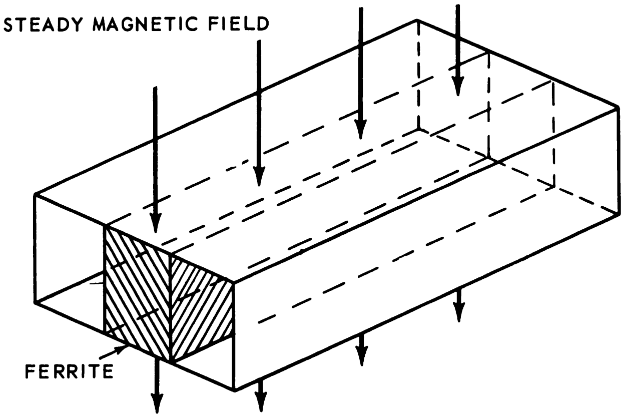
**Ferrite Materials**

Ferrites are unique in that they have useful magnetic properties, and, at the same time, high resistance to current flow. This combination is not found in conventional ferromagnetic materials. Iron, for example, has good magnetic properties but a relatively low resistance to current flow. The low resistance enhances current flow in iron, which causes significant eddy currents and their associated power loss at high frequencies. On the other hand, the ferrites' resistance is high enough for them to be classed as semiconductors. Ferrites that are used at high frequencies are made of high-dielectric materials that are transparent to microwave energy. Thus, rf energy can pass through ferrites.

Ferrites are made of compounds (normally iron oxide) to achieve the desired characteristic. Added to these compounds are various impurities, mainly consisting of oxides of other elements, to obtain the exact characteristics needed for a particular application. The compounds retain the magnetic properties of the ferromagnetic atom (such as iron, nickel, zinc, and magnesium), but the electrical conductivity of the compound is reduced by the addition of the impurities. The composition of ferrites is comparable with compounds used in semiconductors, which should be familiar to you. Manufacturers use different proportions and types of atoms to produce ferrites with a wide range of magnetic and electrical properties. Ferrites are widely used in computers, television, and magnetic recording tapes, as well as in many other fields.

## FERRITE ATTENUATOR

To attenuate a particular radio frequency and to allow other frequencies to pass with little attenuation, a ferrite is placed in the center of a waveguide. The ferrite is positioned so that the electron's magnetic field is perpendicular to the rf energy in the guide (fig. 5-50). Thus, the rf energy will be applied in the torque axes of the spinning electrons. The electrons are precessing at a resonant frequency before the rf energy is felt. If the rf energy has the same frequency as the resonant precessional frequency of the electron, the precession becomes greater because of the rf force. The phase of the rf energy will always be adding to the precession of the electron. Since the electron's spin axis is moved during precession, energy is used. This energy must come from the force causing the increase in precession, which is the rf wave. Hence, the rf energy is attenuated by the ferrite and is given off as heat. If the wave is not at the electron's resonant frequency, energy is still absorbed from the wave when it increases precession. But the wave and the electron's precession have different frequencies; consequently, the wave also reduces the electron's precession. This is determined by the phase relationship between the fields of the two frequencies. When the electron precession is reduced, the wave extracts energy from the electron's magnetic field. Thus, there is only a slight attenuation of the rf energy. The resonant frequency of electron precession may be varied over a limited range by changing the strength of the applied dc field.



92.79

Figure 5-50.—Ferrite attenuator.

## NONRECIPROCAL ISOLATOR

An electromagnetic wave traveling down a waveguide produces, at a point off the centerline of the guide, a rotating magnetic field. This is shown in figure 5-51. When the wave is moving from right to left, the magnetic field at a stationary location, A, will be pointing up, as shown. As the wave pattern moves along so that point 2 is at A, the magnetic field is directed right. Similarly, as points 3 and 4 on the wave arrive at A, the field direction will appear to rotate clockwise. Thus, any point off the center of the waveguide will see a rotating magnetic field as the electromagnetic wave goes by. By applying the same analysis, as shown in figure 5-51, to a wave traveling from left to right, we can demonstrate that the magnetic field at A will now rotate counterclockwise.

A piece of ferrite can be placed in the waveguide at A, as shown in figure 5-52. The dc magnetic field is applied, and either the magnetic field strength or the microwaves frequency is adjusted to make the ferrite's electron resonant frequency equal to the microwave frequency. Now, if a wave travels down the guide from left to right, it will act as a rotating force on the electrons in the iron atoms in the direction of natural precession. The precession builds up to a very high amplitude and causes the power to be absorbed from the electromagnetic wave, to be dissipated in the ferrite as heat.

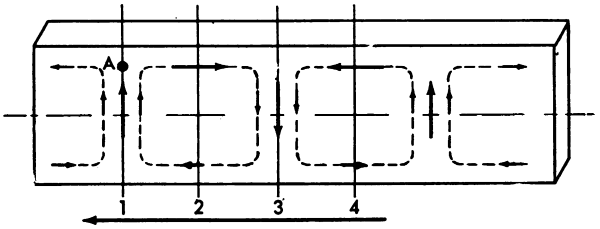


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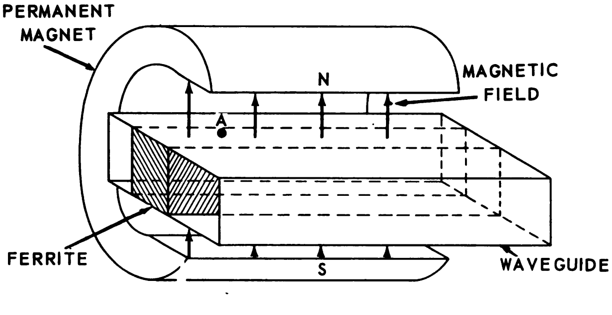
Figure 5-51.—Rotating magnetic field at point A.



92.81

Figure 5-52.—Nonreciprocal isolator.

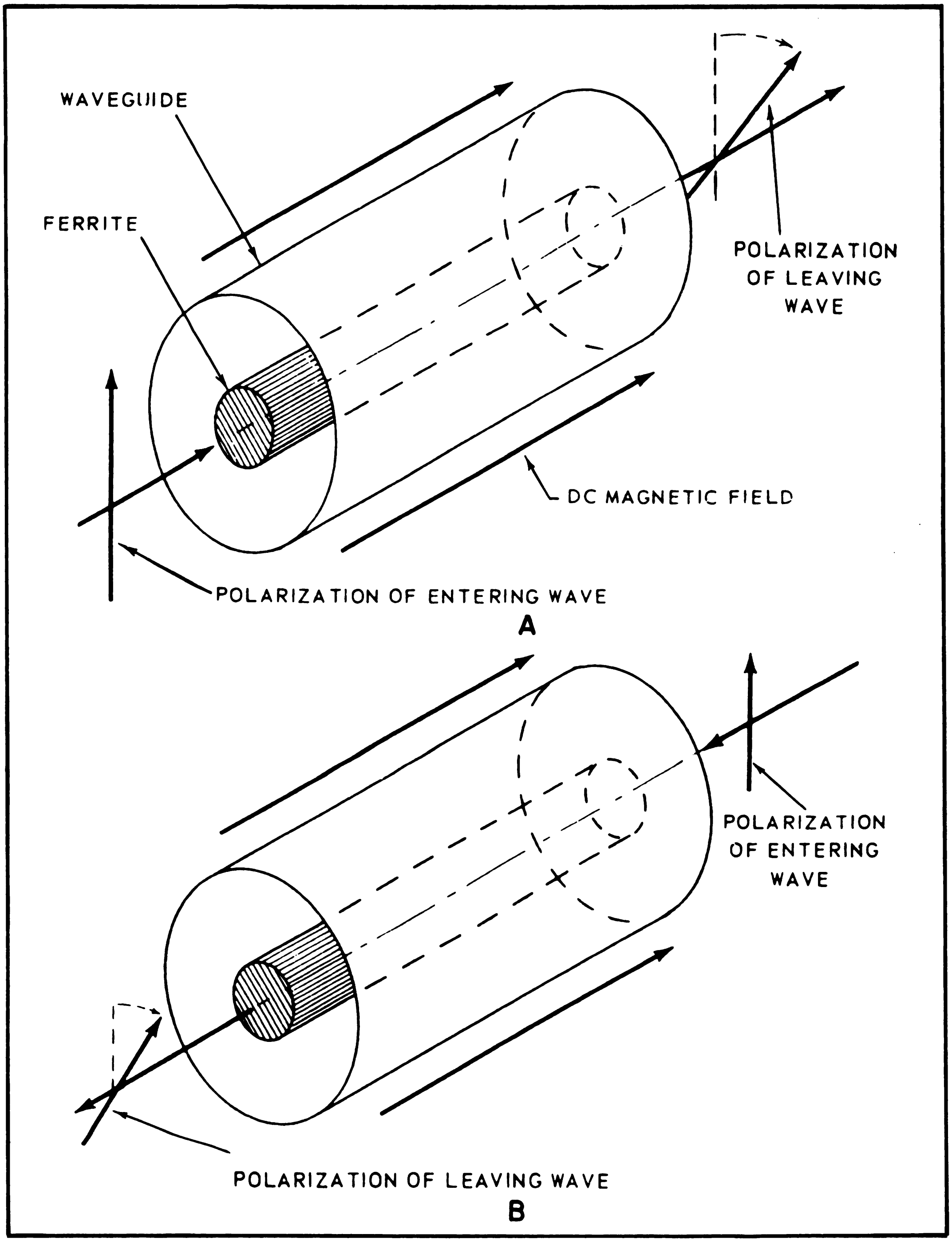
A wave traveling from right to left does not suffer much attenuation. Its rotating magnetic field attempts to push the electrons around in the opposite direction to their natural precession, and no large movements will occur. Thus, a wave traveling from left to right suffers as much as a 10-decibel attenuation, but one traveling from right to left loses only about 0.4 decibel.

## FARADAY ROTATION

When microwaves are passed through a piece of ferrite in a magnetic field, another effect occurs. If the frequency of the microwaves is well above the electron resonant frequency, the plane of polarization of the wave will be rotated. This is known as the Faraday rotation effect (fig. 5-53). A rod of ferrite is placed along the axis of the waveguide, and a dc magnetic field is set up along the axis by a coil. Suppose a wave entering at the left end is vertically polarized. As it enters the section containing the ferrite, it sets up limited precession motion of the electrons. The magnetic fields of the wave and the precessing electrons interact, and the polarization of the wave is rotated. Upon leaving the ferrite, the wave is polarized at a 45-degree angle if we have used the correct length of ferrite.

A more accurate explanation of the Faraday rotation may be made by considering the linearly polarized wave as the sum of two circularly polarized waves rotating in opposite directions. The component wave that is rotating in the same direction as the natural precession motion of the ferrite electrons has some of its energy absorbed, while the counter rotating component will not lose energy. This causes the velocity of propagation for the former component to be somewhat less than for the latter, and the plane of polarization is rotated in the direction of the faster moving wave. For any type of ferrite, the angle of rotation is proportional to ferrite length and the strength of the dc magnetic field; it does not depend on frequency.

The most important effect of the Faraday rotation is that the direction of rotation depends only on the electron spin in the ferrite, so that a


WAVEGUIDE
FERRITE
POLARIZATION OF LEAVING WAVE
DC MAGNETIC FIELD
POLARIZATION OF ENTERING WAVE
A
POLARIZATION OF ENTERING WAVE
POLARIZATION OF LEAVING WAVE
B

92.82

Figure 5-53.—Faraday rotation.

wave going past the ferrite rod shown in figure 5-53 will always be twisted as shown, regardless of which direction it is traveling. The direction of rotation may be changed by reversing the dc magnetic field in the ferrite.

## FERRITE ISOLATOR

A practical device using the Faraday rotation is shown schematically in figure 5-54. A plane-polarized wave comes down the guide and goes through a rectangular-to-round waveguide transition. As the wave passes the ferrite, its plane of polarization is rotated 45° clockwise and enters the rectangular output waveguide, as shown in figure 5-54, view A. However, if a wave comes down the guide in the reverse direction, it will also be rotated 45° clockwise, as shown in figure 5-54, view B, and will be at 90° to the plane of the rectangular output waveguide. The waveguide cannot accept this cross-polarized wave, and the energy will be reflected. Properly oriented vane-type absorbers absorb this energy without affecting waves traveling in the forward direction.

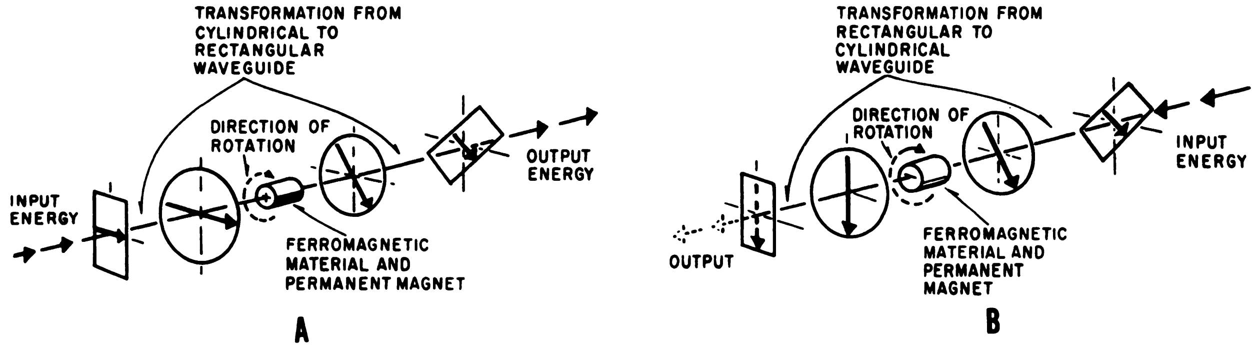
In isolators designed to handle high power, the reflected wave—after its polarization is rotated—can be coupled out to a separate power-absorbing load. An isolator of this type is shown in figure 5-55.

Isolators of the Faraday rotation type are capable of handling more power than the ferromagnetic resonance type, since the reflected energy does not have to be dissipated in the ferrite. Some modern isolators of the Faraday rotation type can provide 30-decibel attenuation in the reverse direction for only 0.1 decibel forward loss. The most important use of one-way isolators is to keep reflected energy (standing waves) from the transmitter. This isolator acts as a switch and is often referred to as a ferrite switch.

This type of one-way isolator can normally be installed in the radar's waveguide system as a unit. The dc magnetic field is established along the ferrite's axis by a permanent magnet. The input and output waveguide flanges of the unit have a 22.5-degree twist.

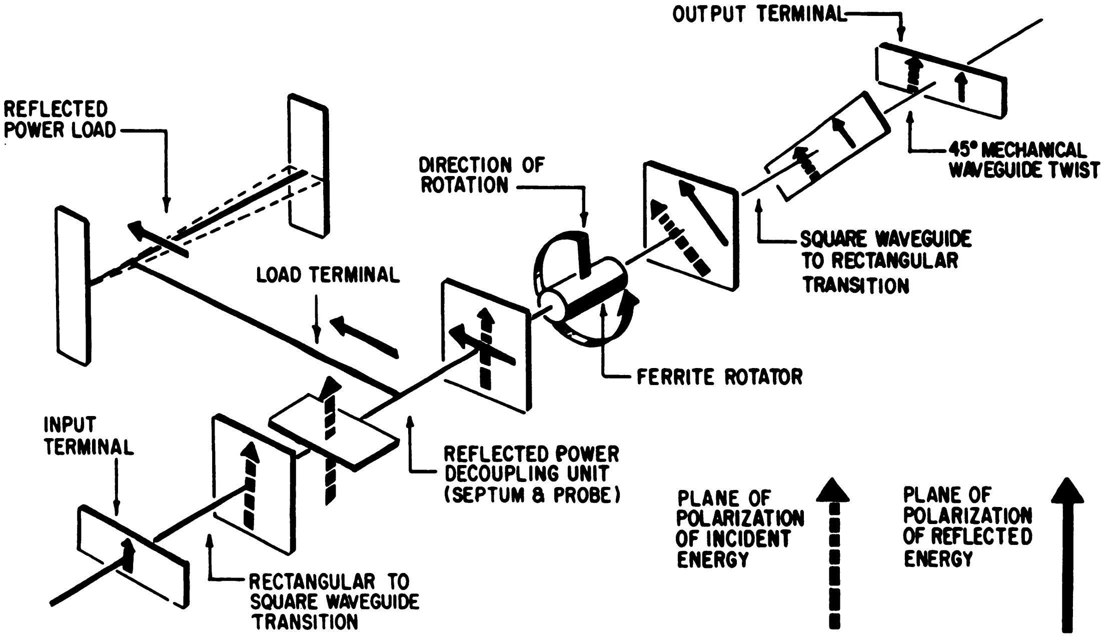
## VARIABLE ATTENUATOR

A variable ferrite isolator uses an electromagnet around the guide, as shown in figure 5-56. A wave, entering the left side, comes in polarized with its E-lines horizontal as shown. If there is no coil current, it will pass the ferrite with no rotation and suffer 3-decibel attenuation in entering the rectangular output guide that is mounted at a 45-degree angle. If current flows through the magnetizing coil in one direction, the ferrite will twist the wave polarization 45° to the left, and it will enter the output guide with almost no loss. Coil current in the opposite direction will twist the wave polarization to the right, and the wave cannot enter the output guide. The wave is


TRANSFORMATION FROM CYLINDRICAL TO RECTANGULAR WAVEGUIDE
DIRECTION OF ROTATION
OUTPUT ENERGY
INPUT ENERGY
FERROMAGNETIC MATERIAL AND PERMANENT MAGNET
A
TRANSFORMATION FROM RECTANGULAR TO CYLINDRICAL WAVEGUIDE
DIRECTION OF ROTATION
INPUT ENERGY
OUTPUT
FERROMAGNETIC MATERIAL AND PERMANENT MAGNET
B

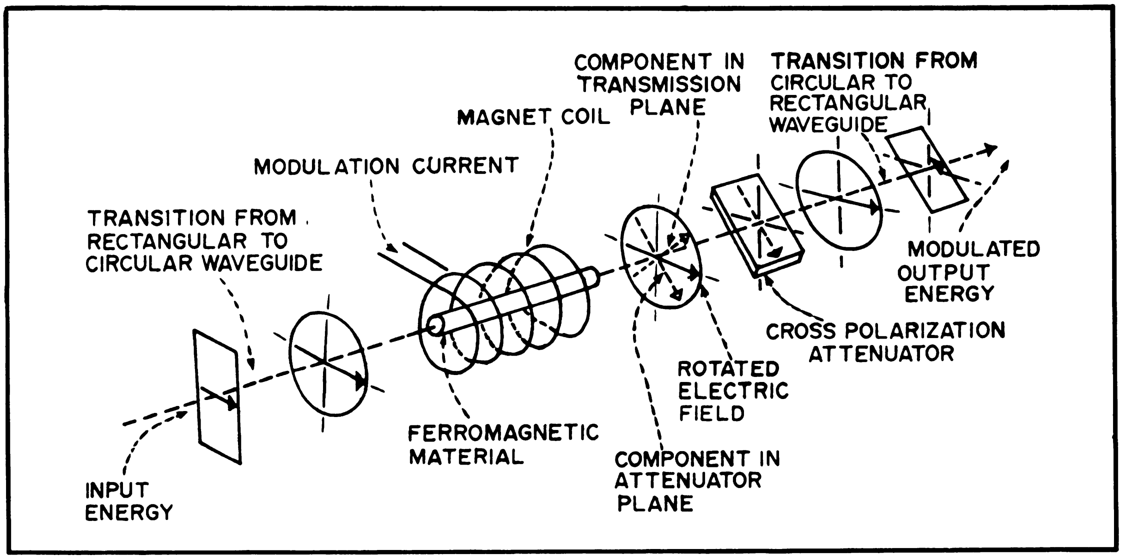
92.83

**Figure 5-54.—Ferrite isolator: A. Wave traveling in the forward direction; B. Wave traveling in the reversed direction.**


OUTPUT TERMINAL
REFLECTED POWER LOAD
DIRECTION OF ROTATION
45° MECHANICAL WAVEGUIDE TWIST
SQUARE WAVEGUIDE TO RECTANGULAR TRANSITION
LOAD TERMINAL
FERRITE ROTATOR
INPUT TERMINAL
REFLECTED POWER DECOUPLING UNIT (SEPTUM & PROBE)
PLANE OF POLARIZATION OF INCIDENT ENERGY
PLANE OF POLARIZATION OF REFLECTED ENERGY
RECTANGULAR TO SQUARE WAVEGUIDE TRANSITION

92.84

Figure 5-55.—Ferrite isolator with separate, reflected-power-absorbing load.


COMPONENT IN TRANSMISSION PLANE
TRANSITION FROM CIRCULAR TO RECTANGULAR WAVEGUIDE
MAGNET COIL
MODULATION CURRENT
TRANSITION FROM RECTANGULAR TO CIRCULAR WAVEGUIDE
MODULATED OUTPUT ENERGY
CROSS POLARIZATION ATTENUATOR
ROTATED ELECTRIC FIELD
FERROMAGNETIC MATERIAL
COMPONENT IN ATTENUATOR PLANE
INPUT ENERGY

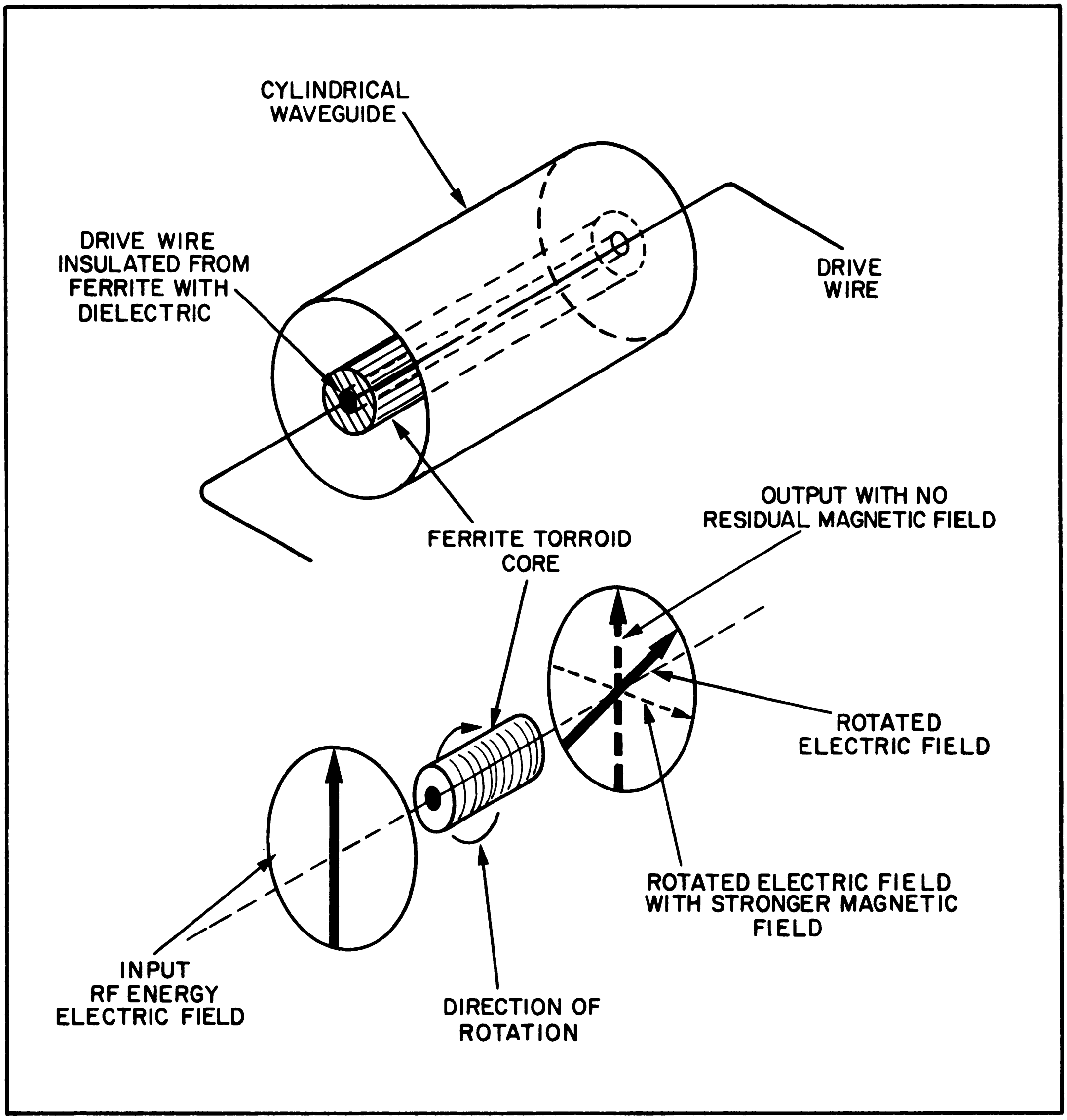
92.85

Figure 5-56.—Ferrite isolator with variable attenuation.

reflected and absorbed by the cross-polarization vane attenuator. This permits the attenuation of a wave to be varied from 0.1 to 30 decibels merely by changing coil current.

This device can be used to produce an amplitude-modulated microwave output merely by feeding the magnetizing coil with the output of an audio amplifier. It permits a constant frequency and amplitude wave to be amplitude modulated with no attendant frequency modulation.

Another important application is in the receiver section of a radar set. A variable attenuator can be placed just before the receiver's crystals. When the transmitter pulse is about to be generated, a step current can be applied to the variable attenuator to cause maximum attenuation. This protects the crystals before


CYLINDRICAL WAVEGUIDE
DRIVE WIRE INSULATED FROM FERRITE WITH DIELECTRIC
DRIVE WIRE
FERRITE TORROID CORE
OUTPUT WITH NO RESIDUAL MAGNETIC FIELD
ROTATED ELECTRIC FIELD
ROTATED ELECTRIC FIELD WITH STRONGER MAGNETIC FIELD
INPUT RF ENERGY ELECTRIC FIELD
DIRECTION OF ROTATION

92.82.1

Figure 5-57.—Ferrite phase shifter.

the transmitter pulse hits them. After the pulse, the attenuation can be reduced slowly, protecting the crystals from strong reflections from nearby objects and providing sensitivity time control (STC) as the range increases. This type of attenuator cannot, of course, protect the crystals from the *main* bang that may enter the antenna from another nearby radar set.

## PHASE SHIFTERS

Before the development of microwave ferrite devices, phase shifters in radar systems were purely mechanical. The output phase of a phase shifter was made to vary by changing the length of the waveguide. This process was mechanical and relatively slow. Now, with the newer phase shifters that use ferrite or semiconductor diodes, the electrical line length is made to vary, which changes the output phase. The newer devices make possible phased-array systems with phase shifters that control the beam steering.

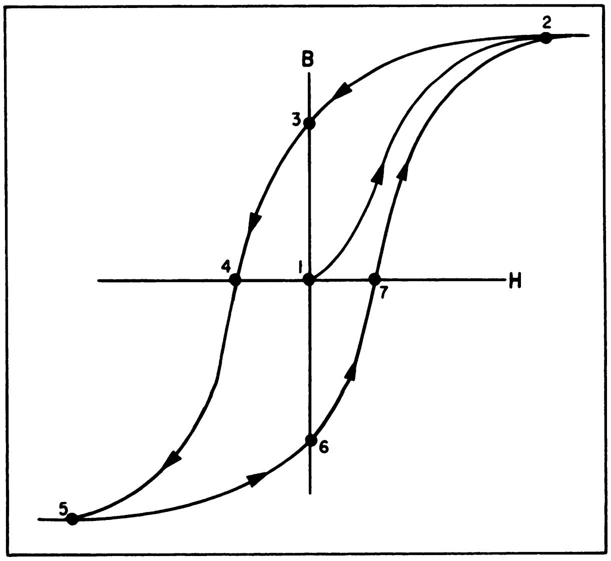
### Ferrite Phase Shifters

The ferrite phase shifters make use of the Faraday rotation principle just as the isolators and attenuators just discussed. The ferrite material is usually made of a garnet type of material. Garnet is composed of an iron oxide with gadolinium, yttrium, and aluminum added to increase the magnetic properties. The garnet material has advantages over most ferrite materials because of a much better temperature stability and higher power handling capability. However, the insertion loss is higher with garnet than other ferrites. When a dc magnetic field is applied to the garnet, the magnetic domains align just as with other ferrites. A difference occurs when the field is removed. With garnet there is a much larger residual magnetism (domains remaining aligned) and resulting magnetic field remaining. This residual magnetism is used to rotate the electromagnetic field. The strength of the residual magnetism determines the amount of phase shift. Phase shifters with as much as 360° of phase shift are currently in use.

### Antenna Phase Shifter

In figure 5-57, a basic ferrite phase shifter is shown. The ferrite core of the shifter is constructed of a hollow cylinder that acts like a digital computer memory core. The core magnetization can be switched from one direction to the other by reversing the current in the drive wire. When a large enough current is carried through the drive wire, all of the possible ferrite core domains align in the same direction. When the drive current is removed, the core remains magnetized in the same direction with only a slight reduction in flux density.

A B-H curve (hysteresis loop) for a typical ferrite material is shown in figure 5-58. The B is the amount of magnetization, and H is the magnetizing force of the applied magnetic field. Point 1 (fig. 5-58) represents a demagnetized core state with no current applied to the drive wire. When current begins to flow, a magnetic field (H) builds around the drive wire and begins to align the domains, causing an increase in the magnetism. (B). At point 2, the applied magnetic field (H) has caused all of the available domains to align. No further increase in magnetism is possible because of saturation, and increasing H will not cause any change in B. When the drive wire is deenergized, H will go to zero, but the magnetism will decrease only slightly to point 3. Applying a reversed current to the drive wire starts increasing the



55.435

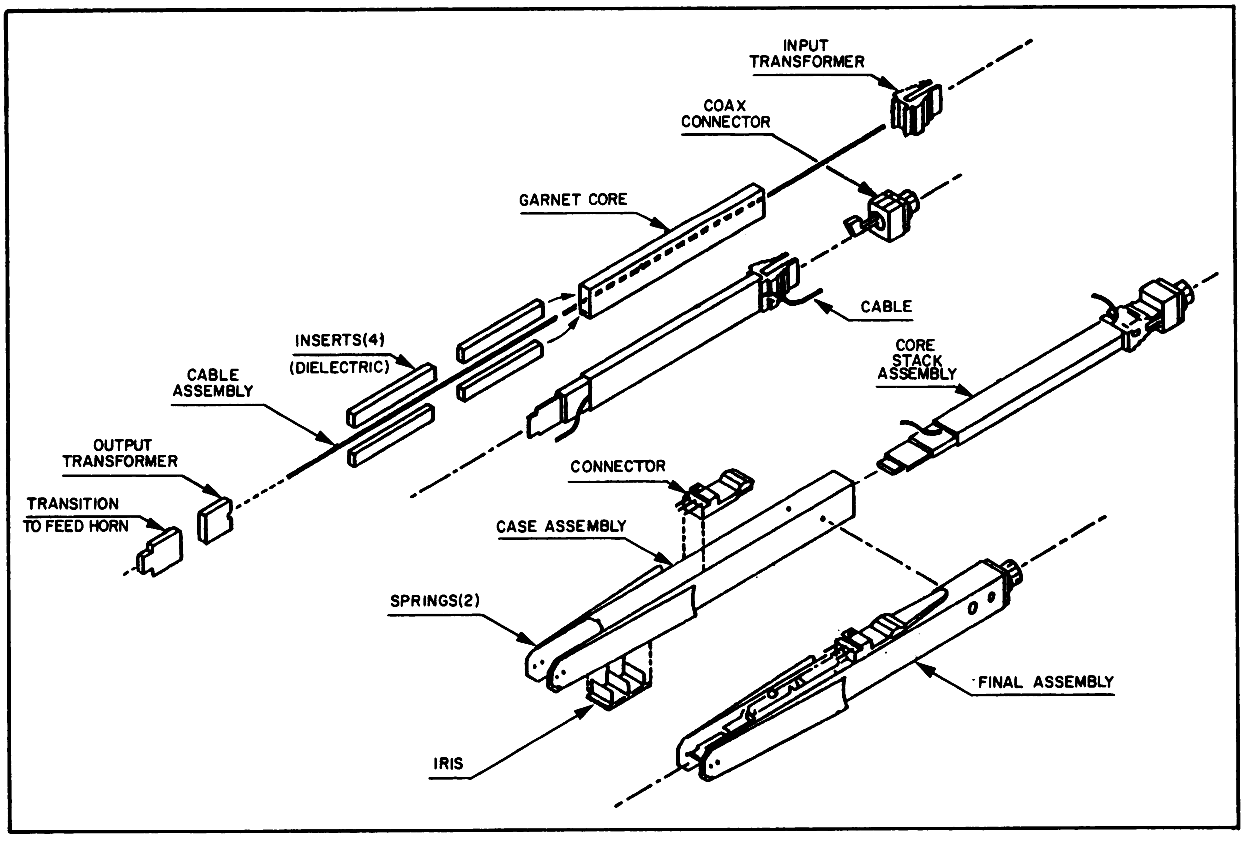
Figure 5-58.—Ferrite B-H curve.

magnetizing force (H) applied in the opposite direction and begins reducing the magnetism (B) until the magnetizing force causes B to reverse also (point 4). Increasing H further will increase B in the opposite direction until saturation (point 5) occurs. Deenergizing the drive wire will reduce H to zero, and B will decrease slightly to point 6. Points 3 and 6 are equal but have opposite polarity. Reversing current again will produce the curve 6 to 2 by way of point 7 in the same sequence that 3 to 5 occurred. Points 3 and 6 represent maximum residual magnetism, and with a ferrite core in either state, maximum phase shift will occur for both a given length of core material and the rf field traveling in the correct direction.

A phase shifter constructed as shown in figure 5-57 and having a B-H curve similar to figure 5-58 is nonreciprocal. The core is switched to one state or to the other, depending on which direction the rf field will travel. An example of this is transmitting and receiving with a phased-array antenna.

In figure 5-59, an exploded view of a nonreciprocal phase shifter for a phased array is shown. The garnet core is constructed in rectangular shape and has four dielectric inserts that support the two-wire drive cable assembly.

The input transformer matches the coax and the ferrite polarizations, and the output transformer matches the ferrite and feed horn polarizations. The rf propagation through the phase shifter will be in either direction—coax to the transition piece for transmit cycle and reversed for the receive cycle. The garnet core is mounted in a circular polarized case assembly. The use of the phase shifter with a phased array makes use of more than one fixed amount of phase shift. By using a phase shifter for each feed horn and



55.436

Figure 5-59.—Phase shifter.

by programming different amounts of phase shift, the antenna beam can be steered to the desired angles.

The changes in amount of phase shift are accomplished by partially demagnetizing the core in steps. Figure 5-60 shows the B-H curve and voltage used to control the phase shifter residual magnetism. The core is reset to a saturated condition (maximum phase shift) prior to the transmit or receive cycle. A computer-generated signal will then determine what amount of phase shift is required and control the driver receive or transmit set pulse duration (figure 5-60, view B). The set pulse from the driver is the opposite polarity from the reset pulse, but it has the same amplitude. The pulsewidth of the set pulse determines how much the residual magnetism is reduced. The set pulse causes the magnetism to decrease (fig. 5-60, view A, points a and c) until the pulse ends, at which time the core returns to a value of residual magnetism less than the maximum (fig. 5-60, view A, points b and d). The reduced magnetism results in a decrease in the phase shift. The set pulsewidths are controlled in 0.125 μsec increments. Each increment represents 22.5° of phase shift change. The phase shifters provide beam steering control of the phased array during transmission and reception by delaying the signals varying amounts. The delay is the result of the rf signal traveling a longer distance while being rotated (phase shifted), as compared to the straight-through path length.

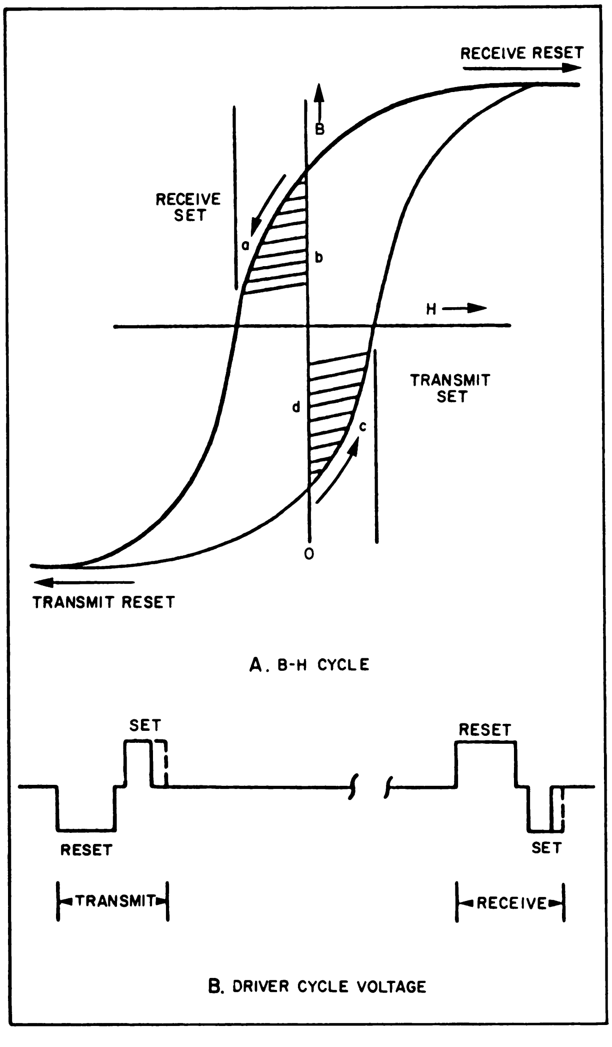


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Figure 5-60.—Phase shifter cycle.

## DUPLEXERS

A single antenna is used for both transmitting and receiving in most fire control radars. This presents a problem, however, of ensuring maximum energy transfer from the transmitter to the antenna and from the antenna to the receiver. A simple solution would be to switch the waveguide from the antenna between the transmitter and the receiver waveguides. This would work; however, at the high repetition rates used by most radars, this method is very impractical. By making use of the waveguide transmission properties of the magic T, directional couplers, hybrid devices, and shorted stub sections, various methods of electronically switching between transmitter and receiver have been developed. These electronic switching devices are known as duplexers. A simple, single-channel radar has a single duplexer, while a multichannel radar receiver may have a duplexer for each channel.

You should already be familiar with basic duplexer operation, as discussed earlier in this chapter. You should also be familiar with NEETS, module 18, and *Basic Electronics*, Volume 2, NAVEDTRA 10087-C. This manual does not describe the basic duplexer operation, but it does describe the operation of a waveguide short-slot hybrid duplexer and several transmit-receive (TR) devices currently used in fire control radars.

The hybrid ring duplexer was described previously in this chapter.

The basic requirements of a radar duplexer are as follows:

- During the period the transmitter pulse is present, it must connect the transmitter to the antenna and isolate the receiver.
- The receiver must be thoroughly isolated during transmission to protect mixer crystals and other sensitive components.
- After the transmitter pulse ends, the duplexer must rapidly connect the receiver to the antenna and disconnect the transmitter.
- The duplexer must have a minimum of loss in both the transmit and receive conditions.

The element of a duplexer that causes the switching action is a transmit-receive tube, or TR tube. Some duplexers use an additional TR device to disconnect the transmitter called an ***antitransmit-receive tube***, or ATR tube. While the TR devices perform the actual switching function, the duplexer itself controls the directions of rf signal flow.

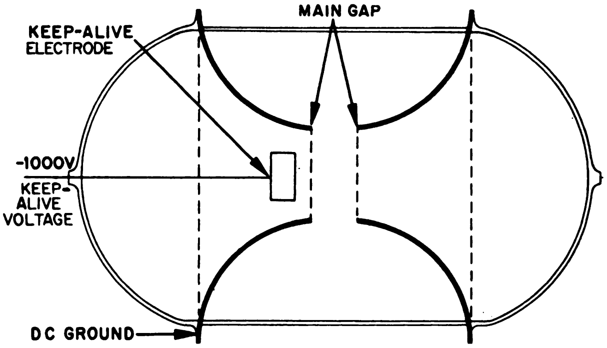
## TR TUBE

The spark gap used in a given TR system may vary from a simple one formed by two electrodes placed across the transmission line to one enclosed in an evacuated, glass envelope with special features to improve operation. The requirements of the spark gap are high impedance prior to the arc and very low impedance during arc time. At the end of the transmitted pulse, the arc should be extinguished as rapidly as possible to remove the loss caused by the arc and to permit signals from nearby targets to reach the receiver.

A simple gap formed in air has a resistance during conduction from 30 to 50 ohms. This is usually too high for use with any but an open-wire transmission line. The time required for the air surrounding the gap to completely deionize after the pulse voltage has been removed is about 10 μ sec. During this time, the gap acts as an increasing resistance across the transmission line to which it is connected. However, in a TR system using an air gap, the echo signals reaching the receiver beyond the gap will be permitted to increase to half their proper magnitude (3 μsec) after the pulse voltage has been removed. This interval is known as recovery time.

TR tubes are conventional spark gaps enclosed in partially evacuated, sealed glass envelopes (fig. 5-61). The arc is formed as electrons are conducted through the ionized gas or vapor. The magnitude of voltage necessary to break down a gap may be lowered by reducing the pressure of the gas that surrounds the electrodes. There is an optimum pressure that achieves the most efficient TR operation. The recovery time, or *deionization* time, of the gap can be reduced by introducing water vapor into the TR tube. A TR tube containing water vapor at a pressure of 1 mm of mercury recovers in 0.5 μsec. It is important for a TR tube to have a short recovery time to reduce the range at which targets near the radar can be detected. If, for example, echo signals reflected from nearby objects return to the radar before the TR tube has recovered, those signals will be unable to enter the receiver.

TR tubes used at microwave frequencies are built to fit into the waveguide system. The speed that the gap breaks down after the transmitter fires may be increased by placing a voltage across the gap electrodes. This potential is known



55.106.1

Figure 5-61.—TR tube with keep-alive electrode.

as *keep-alive* voltage and ranges from − 100 volts to − 1,000 volts. A glow discharge is maintained between the electrodes. The term *glow discharge* refers to the discharge of electricity through a gas-filled electron tube. This is distinguished by a cathode glow and a voltage drop much higher than the gas ionization voltage in the cathode vicinity. This action provides for rapid ionization when the transmitter pulse arrives.

## ATR TUBE

The ATR tube is usually a simpler device than a TR tube. An ATR tube might use a pure, inert gas, such as argon, since recovery time generally is not a vital factor. Furthermore, a priming agent, such as keep-alive voltage, is not needed. The absence of either a chemically active gas or a keep-alive voltage results in ATR tubes having a longer life than TR tubes.

## PASSIVE TR LIMITER

The passive TR limiter is similar to the ATR and TR tubes, but it contains a radioactive igniter. The igniter replaces the keep-alive electrode in the TR tube. This igniter keeps a sufficient quantity of electrons available to allow rapid ionization in the presence of the transmit pulse or any nearby transmitter. Unlike the TR tube, the passive TR limiter provides protection even when the radar is off.

## SHUTTERS

As the name implies, shutters are used to close off the waveguide and block rf from reaching the receiver. Shutters are electromechanical devices that are added to a TR tube and act very much like a camera shutter. The shutter can be a metal conductor that shorts out the two electrodes of a TR tube when an electromagnet is deenergized. Shutters will protect a radar receiver when the radar is turned off and no keep-alive voltage is present.

Shutters can also be constructed in waveguide sections. These are used to isolate microwave components for replacement without having to deenergize the whole system.

**WARNING**

**RADIATION HAZARD**

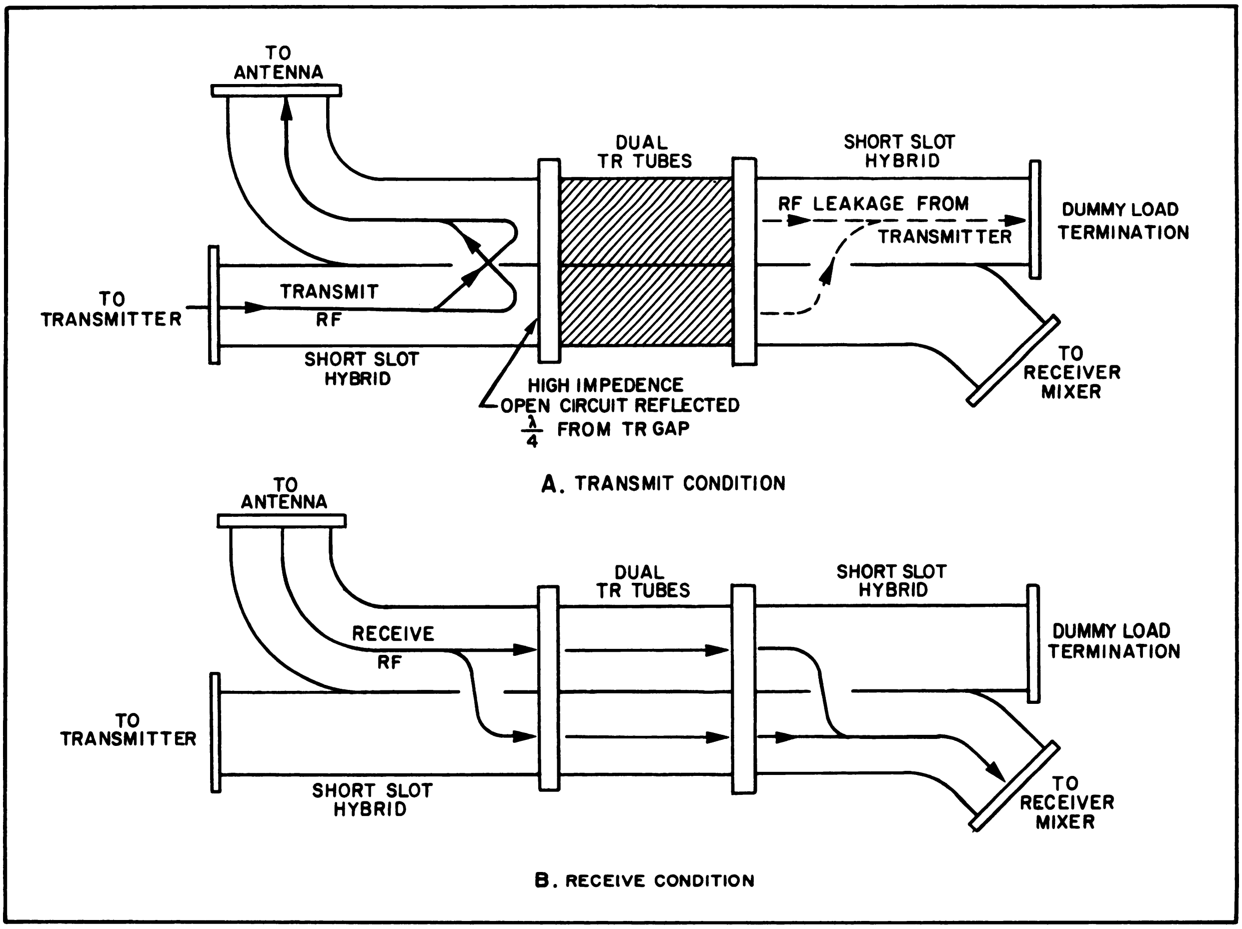
Most TR devices contain radioactive materials and should have the radioactive symbol on the outer case. Care should be used when handling TR devices to prevent breakage and possible contamination. If your equipment contains radioactive TR devices or any other radioactive components, you should be familiar with the correct handling, disposal, and decontamination procedures set forth in *Radiation, The Health Protection Manual*, NAVMED-P-5055.

## BALANCED DUPLEXER

A balanced TR duplexer is shown in figure 5-62. The duplexer consists of two short-slot hybrids and a dual TR tube. The receiver short-slot hybrid has one arm terminated with a dummy load; the other arm is connected to the receiver mixer. The dual TR tubes consist of two TR tubes in a common case that mates to the two hybrids.

In figure 5-62, view A, the duplexer is shown in the transmit condition with both TR tubes firing. The TR arcs reflect a high impedance to the transmitter hybrid that reflects the rf. Both the reflected signals will be in phase and recombine in the hybrid arm leading to the antenna. The small amount of rf leakages through the TR tubes will be phased in such a manner that they will combine in the dummy-load arm of the receiver hybrid and be absorbed and dissipated as heat in the dummy load.

During the receive condition (fig. 5-62, view B), both TR tubes are deenergized (no arc) and offer a low-impedance path to the received rf. The rf divides equally at the transmitter hybrid and is of a phase relationship that causes the two signals to recombine in the receiver mixer arm of the receiver hybrid. The balanced TR duplexer can provide protection to the receiver when the radar is off by adding shutters to both TR tubes.



55.438

Figure 5-62.—Balanced TR duplexer.

## ANTENNAS

Antennas are used to radiate electromagnetic energy into space and to receive electromagnetic energy from space. Antennas act as transition elements that match the impedance of the waveguide transmission line to that of the atmosphere. The characteristics of antennas were briefly described in the previous chapter. Antennas are described in more detail in the following paragraphs.

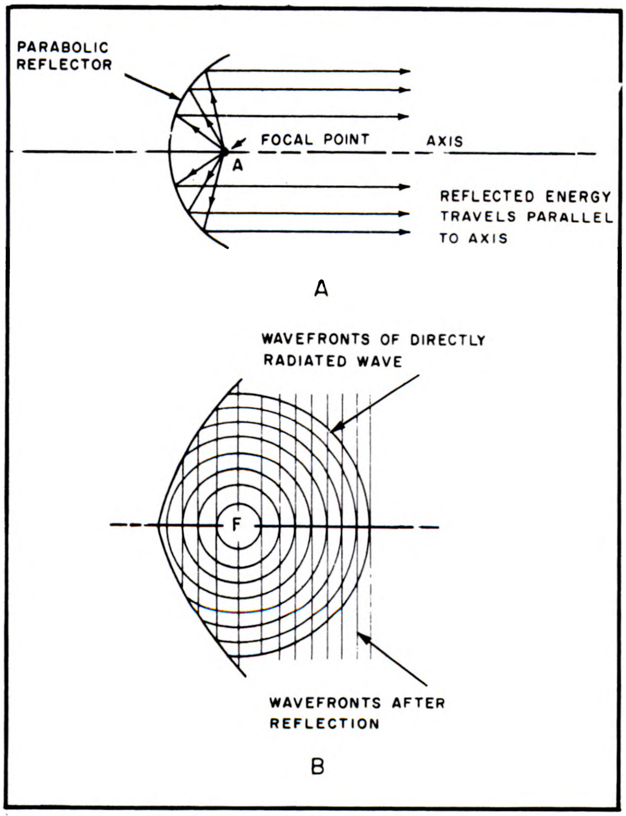
Radar is used in various ways in the solution of the fire control problem. For one thing, it establishes the tracking line. To do this, fire control radars must have high directivity. *Directivity* refers to the sharpness or narrowness of the radiation pattern. Antenna characteristics are a major factor in determining the radiation pattern.

You are probably familiar with some fire control antennas. A brief description of the various types found in the fleet is included in this course, but the actual dimensions of radiated patterns are not included because they are classified. The figures are given in the equipment technical manuals. This manual covers the underlying reasons for the different patterns as determined by antenna configuration. Before proceeding, you should remember that radar energy has a wavelength in the microwave range and has properties similar to those of light waves. For example, rf energy can be reflected and refracted.

## PARABOLIC REFLECTORS

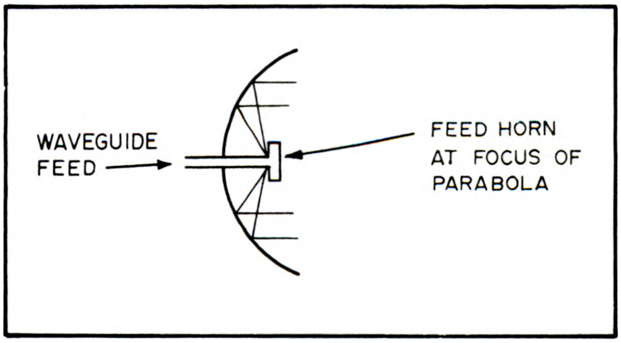
The parabolic reflector is one directional device used at microwave frequencies. If a point source is placed at the focal point A in figure 5-63, view A, the reflector concentrates the radiation from the source into a beam, much as a searchlight reflector concentrates a light beam. The parabola converts the spherical waves, as radiated by the point source, into plane waves (fig. 5-63, view B).

One form of parabolic reflector is the paraboloid of revolution, or rotational parabola. This surface is generated by the revolution of a parabola about its axis; it somewhat resembles an eggshell cut in half at right angles to the long axis. Figure 5-64 shows a cross-sectional view of a rotational parabola, which is excited by a feed horn located at the focal point inside the parabola. The feed horn radiates the rf energy back toward the paraboloid through two apertures (fig. 5-65). By


PARABOLIC REFLECTOR
FOCAL POINT
AXIS
A
REFLECTED ENERGY TRAVELS PARALLEL TO AXIS
A
WAVEFRONTS OF DIRECTLY RADIATED WAVE
F
WAVEFRONTS AFTER REFLECTION
B

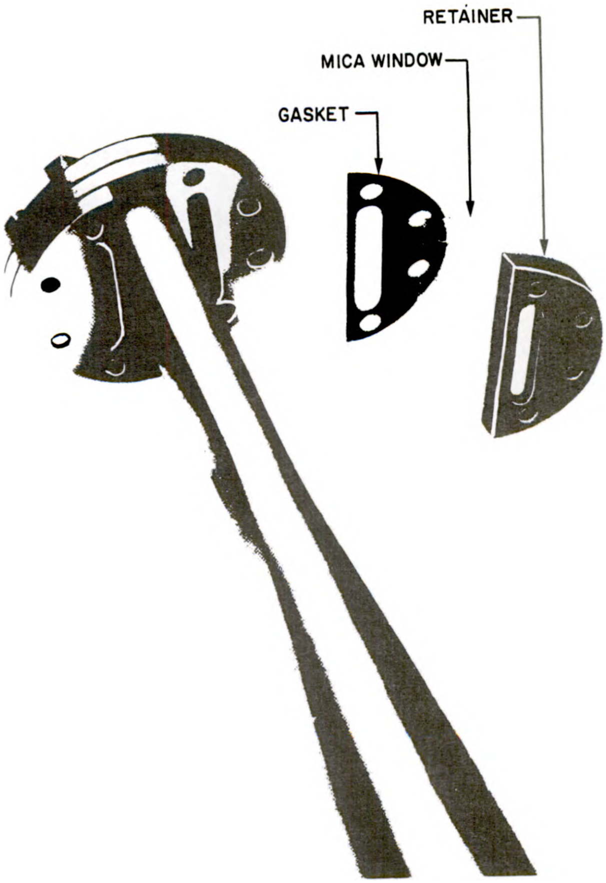
25.226

Figure 5-63.—Parabolic reflector.



13.45

Figure 5-64.—Cross-section of paraboloid.



92.87

Figure 5-65.—Dual aperture rear feed horn (Culter).

this means, direct radiation is eliminated, the beam is made sharper, and power is saved. Without this type of feed, some of the radiated field would leave the radiator directly. Since it would not be reflected, it would not become a part of the main beam, and thus could serve no useful purpose. Another method of accomplishing the same result is through the use of a parasitic array to direct the radiated field back to the reflector.

The radiation pattern of a rotational parabola contains a major lobe, which is directed along the axis of revolution, and several minor lobes, as shown in figure 5-66. Very narrow beams are possible with this type of reflector.

### Truncated Paraboloid

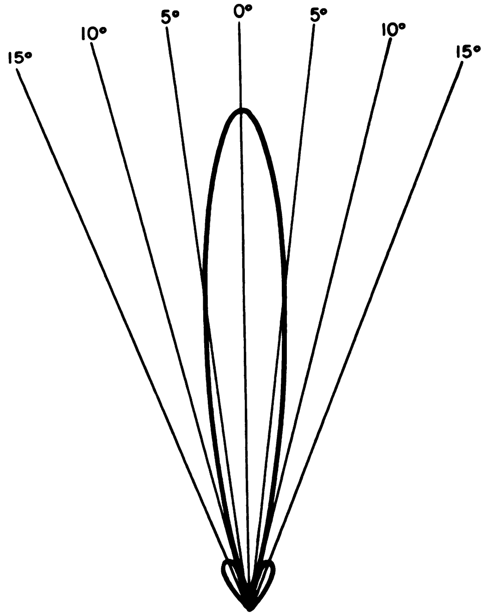
The truncated paraboloid (fig. 5-67) is a section of a full paraboloid. The upper and lower portions of the paraboloid, represented by dashed lines in the illustration, are not used. For the horizontally mounted, truncated parabolic reflector, the width of the horizontal plane beam is essentially the same as it would be without the truncation. Thus, the radiated pattern of the radar is narrow in the horizontal plane. Accurate bearing information is obtained by this type of antenna configuration.

It is practical to construct the reflecting dish in the form of a grate or mesh, rather than a solid surface. You have undoubtedly seen grated reflector dishes. The electromagnetic properties of a grated reflector are similar to those of a solid reflector. The grated dish reflects satisfactorily if the material in the grating lies in the plane of the radiated waves. This plane is determined by the polarization of the antenna feed system. As stated previously, the plane that contains the electric lines of force determines the polarization of the wave.

### Parabolic Twist Reflector

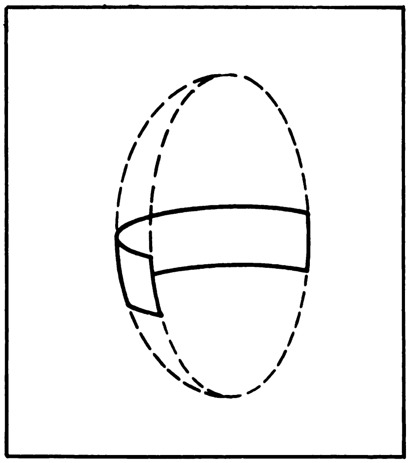
The parabolic twist reflector antenna is also referred to as a *Cassegrainian antenna*. In the antenna, the energy is initially radiated from a point source (for example, a feed horn) and is polarized so that the E-lines are in a definite plane. Assume the waves are horizontally polarized and the grating strips of the reflector in figure 5-68 are aligned parallel in the vertical plane. This surface would be transparent to the wave, and the energy would pass through the dish and not be reflected.

If the grating strips in the reflector dish were rotated so they were in the same plane as the wave,



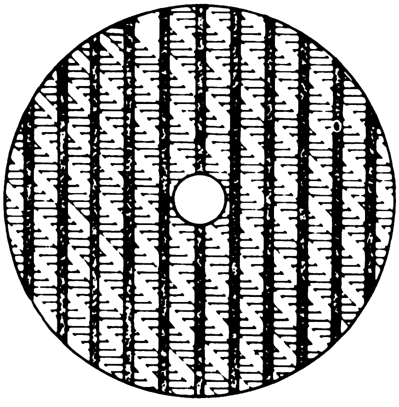
1.257

Figure 5-66.—Pattern of rotational parabola.



25.228

Figure 5-67.—Truncated paraboloid

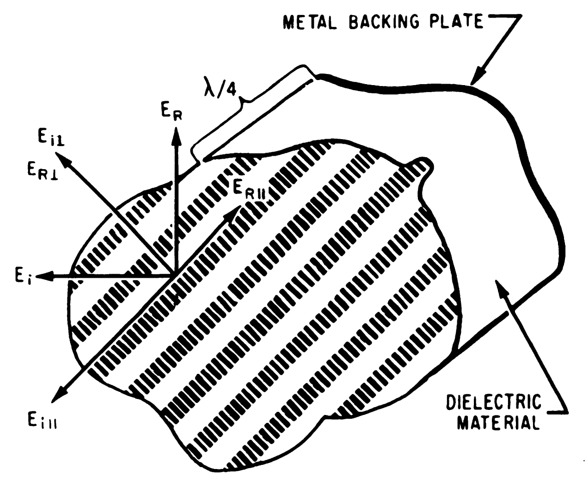


92.89

**Figure 5-68.—Reflector with grating strips in the vertical plane.**

the grate would reflect the wave. The reflected wave is reversed in phase 180°. Although there is a phase reversal, the polarization of the wave does not change. Each point on the reflector can be regarded as a point source of energy. By controlling the contours of the dish, the reflected rays can be made convergent, divergent, or parallel.

Now let's see what would happen if the grating strips were rotated so as to make a 45-degree angle with the wave's plane. The E-fields of the incident energy are resolved into two components, one parallel and one perpendicular to the grating (fig. 5-69). The perpendicular component will pass into the dielectric material, while the parallel component is reflected by the grating. A metal plate, located 1 quarter-wavelength behind the grating, reflects the component that penetrated the dielectric material. This arrangement allows this component of the wave to have the same phase when leaving the dielectric as it had when entering. The component of the wave reflected by the grating is changed 180° in phase. Because of the antenna arrangement, the reflected waves are 90° out of phase with each other. Therefore, when the reflected waves recombine, the resulting polarization (vertical) is perpendicular to the incident polarization (horizontal).



SECTION OF POLARIZATION CONVERTER

**Legend:**

$E_i$ = E-FIELD OF INCIDENT ENERGY
$E_{i\parallel}$ = COMPONENT OF $E_i$ PARALLEL TO THE GRATING
$E_{i\perp}$ = COMPONENT OF $E_i$ PERPENDICULAR TO GRATING
$E_R$ = E-FIELD OF ENERGY REFLECTED FROM POLARIZATION CONVERTER
$E_{R\parallel}$ = COMPONENT OF $E_R$ PARALLEL TO GRATING
$E_{R\perp}$ = COMPONENT OF $E_R$ PERPENDICULAR TO GRATING

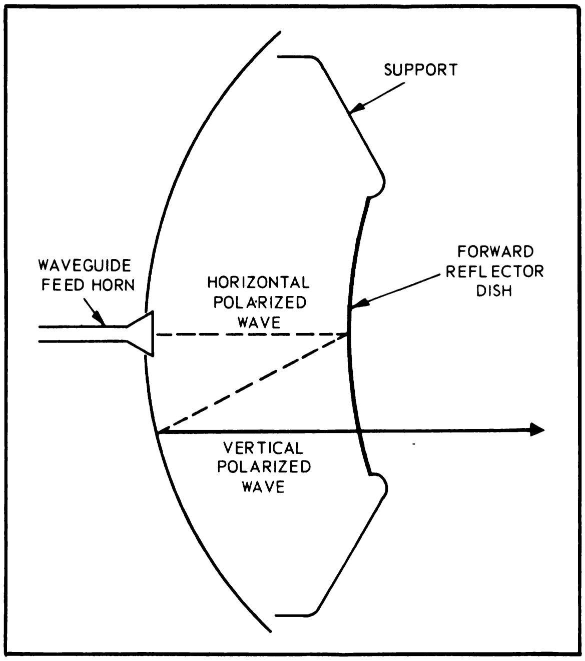
92.90

**Figure 5-69.—Vector representation of polarization conversion.**

From the preceding explanation we know that a grated reflecting surface can be made so that it will transmit a wave with a different polarization. In a Cassegrainian antenna, a reflector dish with grating strips horizontally mounted is placed in front of a parabolic twist reflector (fig. 5-70). The forward reflector is transparent to vertically polarized waves and will reflect horizontally polarized waves. The rf source is horizontally polarized, and its waves are reflected by the forward reflector. The reflected waves strike the twist reflector and are rotated to the vertical plane. The waves can now pass through the forward reflector.

## LENS ANTENNA

At microwave frequencies, the conversion of spherically radiated energy into a wave consisting of mutually perpendicular E- and H-lines (plane wave) in a given direction can be accomplished by using a point radiating source in conjunction with a collimating lens. The point source, which



92.91

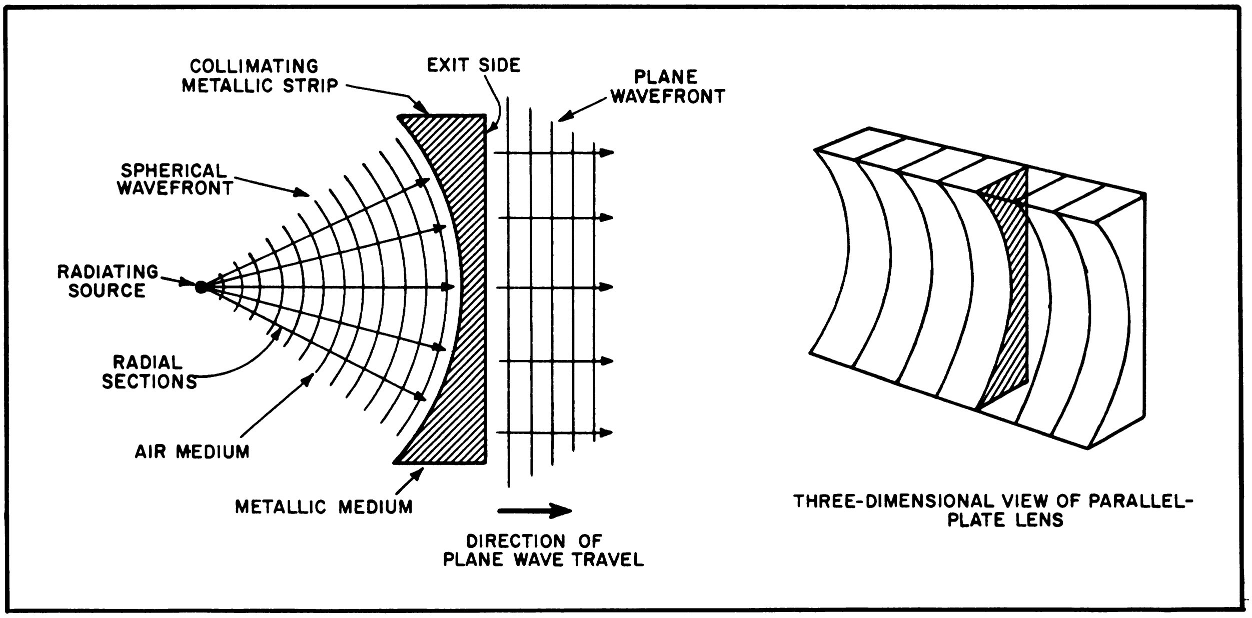
Figure 5-70.—Parobolic twist antenna (Cassegrainian).

is the open end of a waveguide, can be regarded as a gun that shoots the rf energy toward the lens. The antenna, thus formed, is referred to as a *lens antenna*.

The lens (fig. 5-71) consists of several paralleled, concave, metallic strips that are placed parallel to the electric (E) field of the radiated energy fed to the lens. For the incident wave, these strips act as waveguides in parallel. The strips are placed slightly more than a half-wavelength apart.

The radiated energy consists of an infinite number of radial sections or rays. Each of the radial sections contains mutually perpendicular E- and H-lines, both of which are perpendicular to the direction of travel. Because each of the radial sections travels in a different direction, the point source in itself has poor directivity. The purpose of the lens is to convert the input spherical rf segment (which consists of all of the radial sections) into parallel or collimated lines in a given direction at the exit side of the lens. The focusing characteristic of the lens is accomplished through the refracting qualities of the metallic strips.

To understand the collimating effect of the lens, you should consider that the phase velocity


COLLIMATING METALLIC STRIP
EXIT SIDE
PLANE WAVEFRONT
SPHERICAL WAVEFRONT
RADIATING SOURCE
RADIAL SECTIONS
AIR MEDIUM
METALLIC MEDIUM
DIRECTION OF PLANE WAVE TRAVEL
THREE-DIMENSIONAL VIEW OF PARALLEL-PLATE LENS

92.92

Figure 5-71.—Lens antenna.

of the electromagnetic energy propagation through metals is greater than through air. Because of the concave construction of the lens, wavefronts arriving near the ends of the lens are accelerated more than those arriving near the middle. Therefore, the portions of the spherical wavefront near the ends of the lens travel farther than those at the center in the same amount of time. Thus, the wavefront emerging from the exit side of the lens appears as a plane wave, now consisting of an infinite number of parallel sections with both the E-field and H-field components mutually perpendicular to the direction of travel.

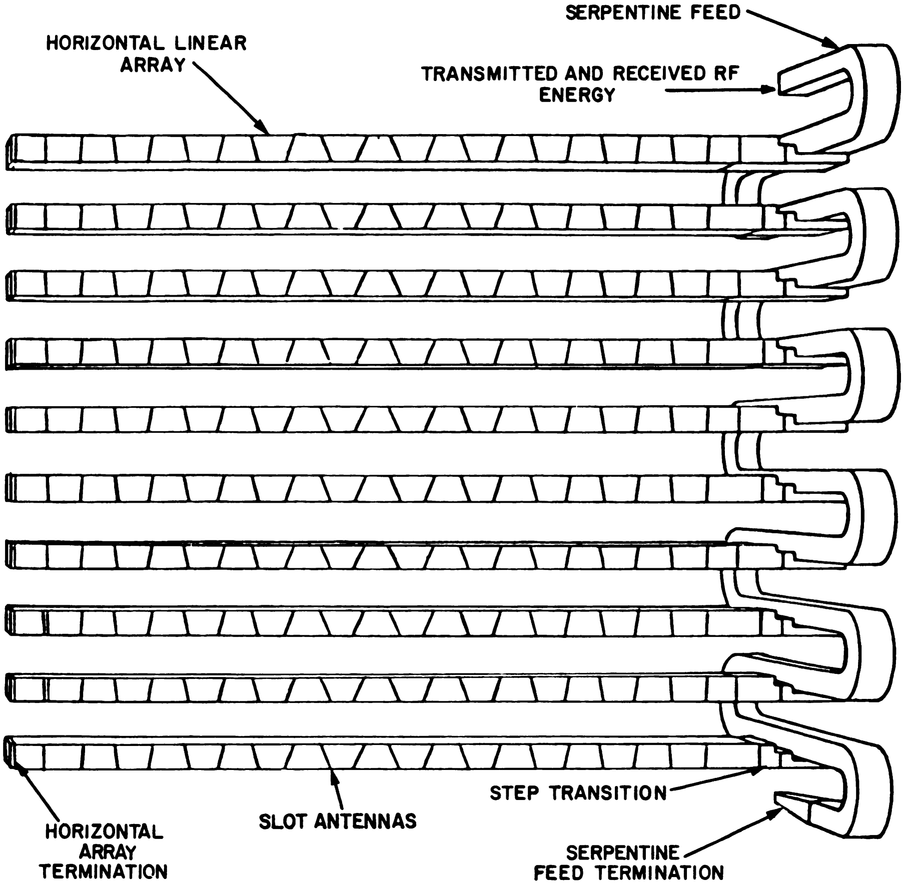
## PHASED ARRAYS

Several different methods of scanning with phased arrays are currently used with radars maintained by FCs. The two primary methods are both similar in how the beams are steered; one uses a phase shifter, the other a frequency change.

### Frequency Controlled Array

This type of radar antenna is frequency sensitive. It radiates rf pulses at an elevation angle determined by the applied rf frequency. When the frequency is increased, the elevation angle decreases. Conversely, when the rf frequency is decreased, the elevation angle increases. Therefore, the elevation transmitted beam angle from the antenna is selected by the application of a signal whose frequency corresponds to the desired angle of elevation.

In figure 5-72, a typical 3-D search radar antenna array is shown. The rf pulse to be


SERPENTINE FEED
HORIZONTAL LINEAR ARRAY
TRANSMITTED AND RECEIVED RF ENERGY
STEP TRANSITION
HORIZONTAL ARRAY TERMINATION
SLOT ANTENNAS
SERPENTINE FEED TERMINATION

167.855

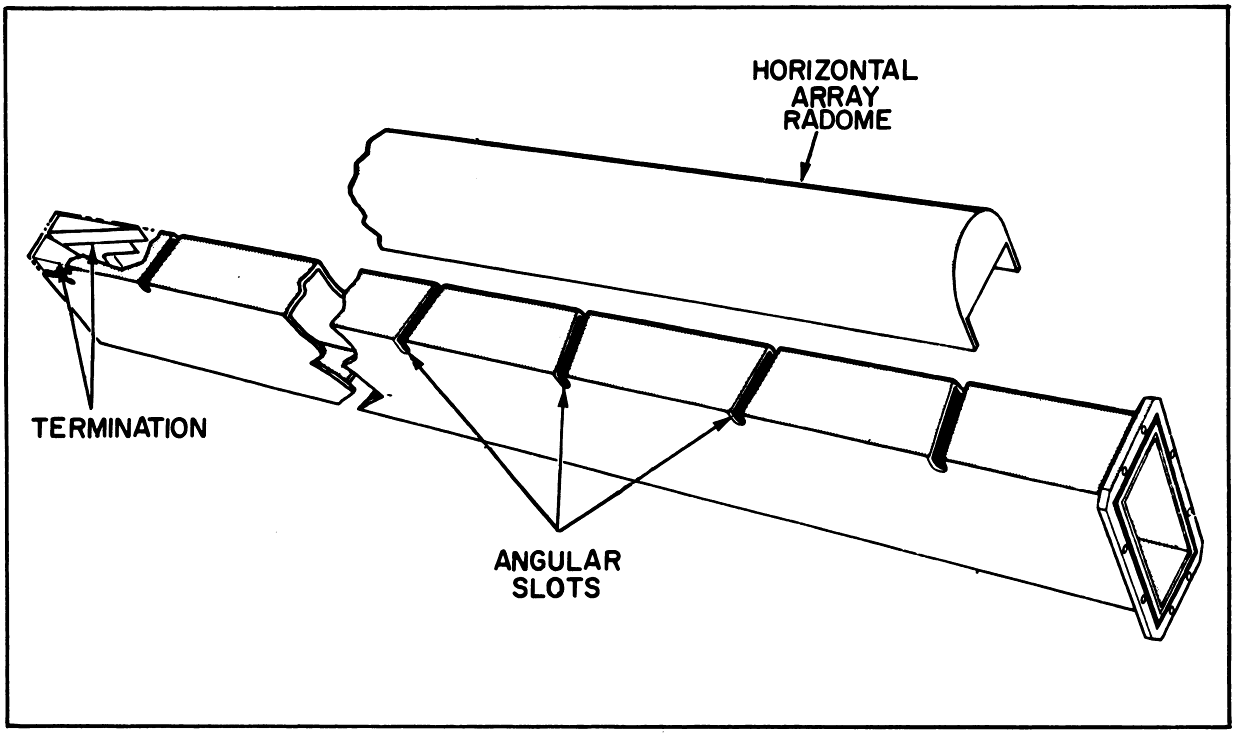
Figure 5-72.—Antenna array.

transmitted is applied to a *serpentine feed*, which is formed by folding a waveguide transmission line back and forth upon itself. The rf pulse is coupled to each horizontal linear array through a short step transition from the serpentine feed. The short step transition contains an rf window that separates the serpentine feed from the horizontal arrays. The serpentine feed is usually pressurized to approximately 30 psig to reduce the potential for arcing in the transmission line and serpentine feed. Waveguide pressurization will be discussed in more detail in the next chapter. The horizontal linear arrays are pressurized only at 1 to 2 psig because the array radomes (fig. 5-73) are composed of thin fiber glass material. The radomes protect the angular slot opening in the horizontal array from weather. The serpentine feed termination at its lower end absorbs any rf energy that is not coupled to the horizontal linear arrays. This prevents reflections of energy within the serpentine feed.

Each horizontal array is a section of waveguide with angular (vertical) slot radiators. Depending upon the antenna design, a group of horizontal arrays are arranged into a planar array and mounted on a rectangular frame. Each horizontal array is terminated with an absorption load that absorbs any rf energy that is not radiated from the angular slot radiators.

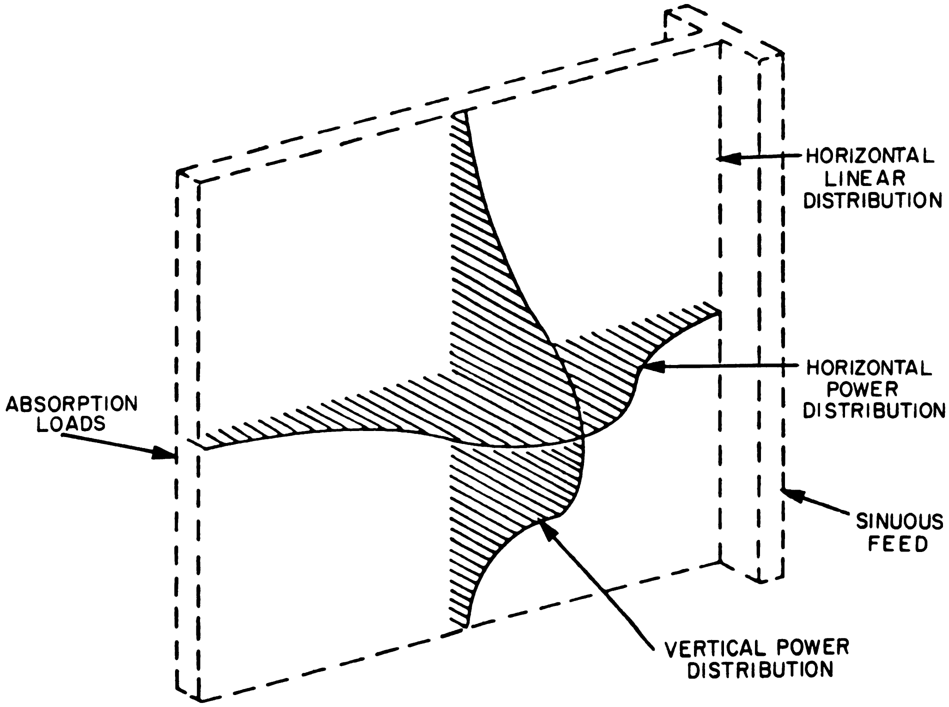
Figure 5-74 shows the power distribution pattern for both horizontal and vertical planes. The power distribution pattern for the horizontal plane is fixed and dependent upon the angular slots within each horizontal array. The vertical power distribution pattern is a function of the feed slot size in the serpentine.

The angle of the rf beam, with respect to the face of the antenna, can be changed only by changing the frequency of the transmitted rf energy. As indicated earlier, when the frequency of the rf energy is increased, the rf beam scans down in elevation; and when the frequency is decreased, the rf beam scans up. A closer look at this relationship is shown in figure 5-75. Assuming that distances $d_1$ and $d_2$, as shown in figure 5-75, view A, are 1 half-wavelength ($\lambda/2$) at the



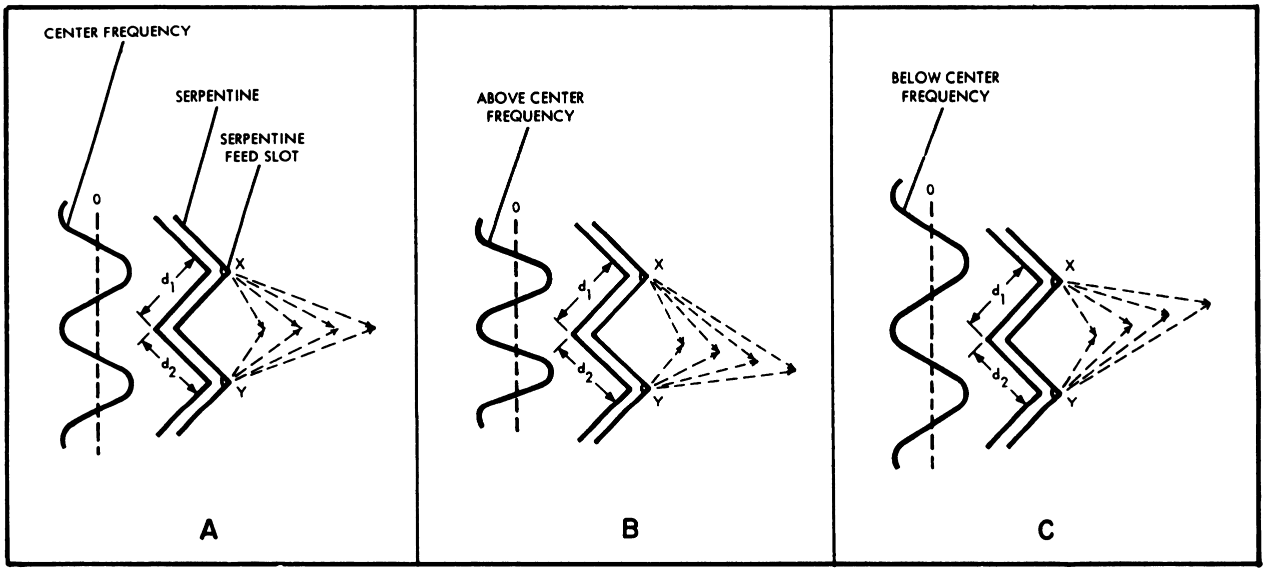
55.439

Figure 5-73.—Horizontal array.


HORIZONTAL LINEAR DISTRIBUTION
HORIZONTAL POWER DISTRIBUTION
ABSORPTION LOADS
SINUOUS FEED
VERTICAL POWER DISTRIBUTION

167.856

Figure 5-74.—Composite power distribution.

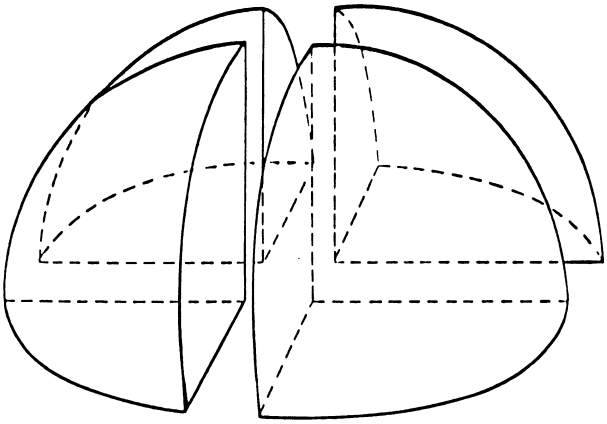


55.440

Figure 5-75.—Frequency vs serpentine phase relationship.

center frequency, the rf energy fed from feed slots X and Y to the horizontal linear arrays is in phase. Maximum reinforcement of the rf energy will be in a plane midway between points X and Y, as indicated by the dashed lines with arrowheads.

When the frequency is increased slightly, as shown in figure 5-75, view B, distances $d_1$ and $d_2$ will not be greater than $\lambda/2$, causing the rf energy at feed slots X and Y to be out of phase. As illustrated, maximum energy will be radiating from feed slot X, and less than maximum energy will be radiating from feed slot Y. Therefore, the greatest algebraic summation will be in a plane similar to that indicated by the arrowheads.



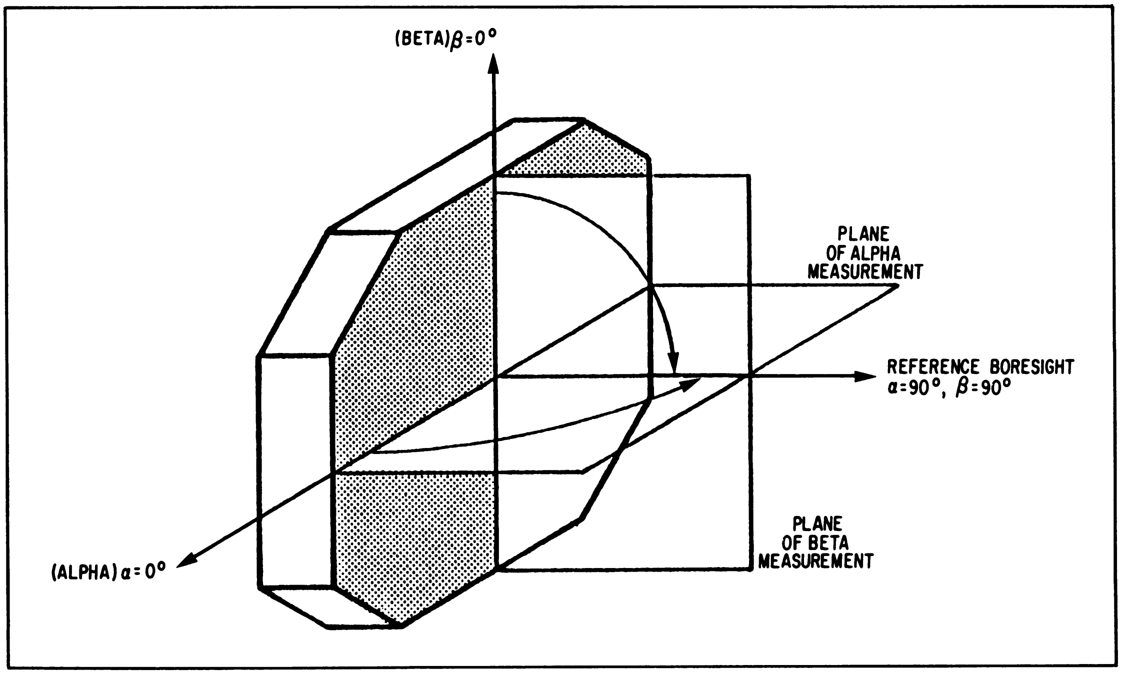
55.441

Figure 5-76.—Hemispherical coverage in four quadrants.

When the frequency is decreased slightly, as shown in figure 5-75, view C, distances $d_1$ and $d_2$ will now be less than $\lambda/2$, causing the rf energy at feed slots X and Y to be out of phase. As illustrated, maximum energy will be radiating from feed slot Y, and less than maximum energy will be radiating from feed slot X. Therefore, the greatest algebraic summation will be in a plane similar to that indicated by the arrowheads.

Only the operation of two feed slots on the serpentine were shown in figure 5-75. In actual operation, all feed slots are affected, causing the phase shift to be accumulative for the total length of the serpentine

With this type of array, the electronic scanning is along the vertical axis only. The beam is scanned horizontally by mechanical rotation of the antenna.


(BETA)β=0°
PLANE OF ALPHA MEASUREMENT
REFERENCE BORESIGHT α=90°, β=90°
PLANE OF BETA MEASUREMENT
(ALPHA) α=0°

55.442

Figure 5-77.—Array coordinates.

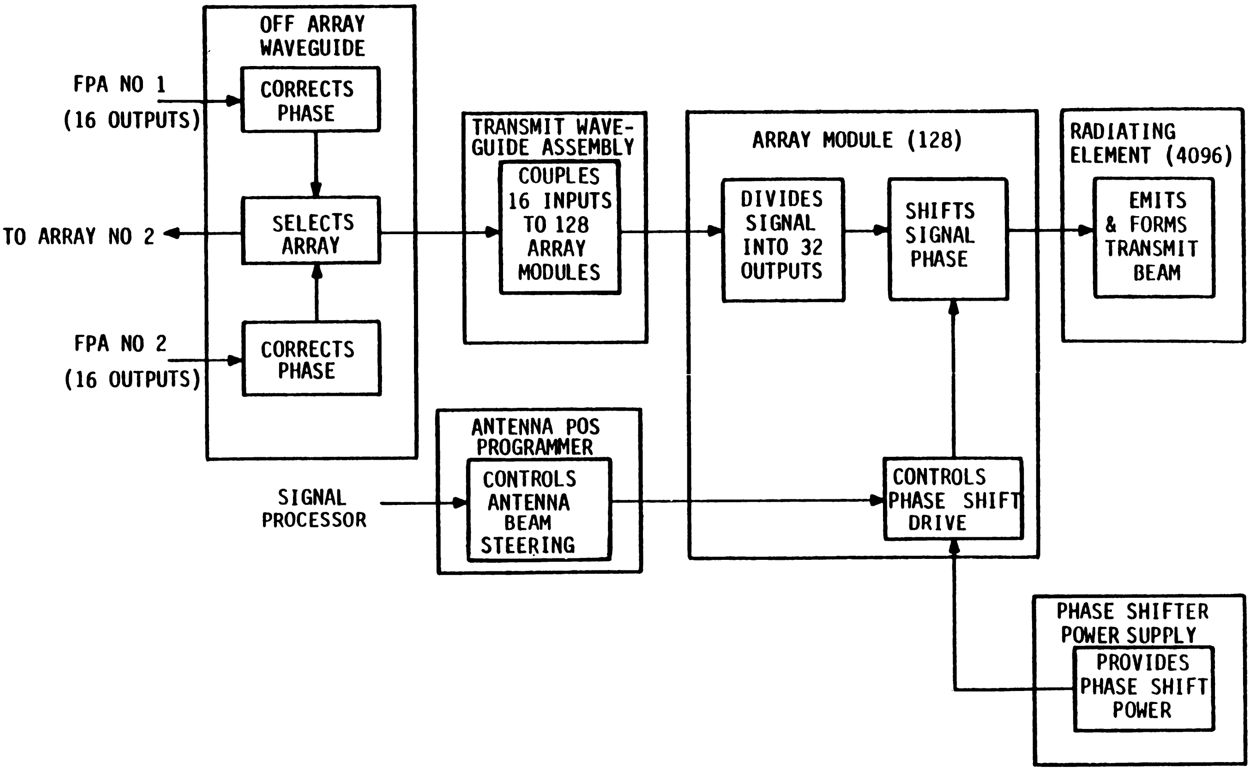
### Phase Controlled Array

With this type of array control, the beam can be steered in two dimensions with no mechanical control of the antenna required. By using the antenna phase shifters previously described, full control of the antenna beam, for both transmission and reception, is accomplished. Four arrays are required for 360° of horizontal coverage. Each array is physically mounted on the ship at an angle of 15° from vertical and 90-degree angles from each other (azimuth angles of 0°, 90°, 180° and 270°). Full hemispherical coverage in four quadrants is shown in figure 5-76.

Each planar array is octagonal in shape and consists of 4,352 horn elements subdivided into 136 modules of 32 horns each. Each horn has a phase shifter with control over the phase for that element. For transmission only, 128 modules (32 horns each) are used. The rf phase of each horn element is computer controlled by way of the phase shifters. The rf phase applied to all of the phase shifters is identical. Beam steering is then accomplished by changing the relative phase, and, thus, the time that the maximum field strength is present at each horn. The wavefront formed on the array face will have a direction that is the vector resultant of all of the individual wavefronts.

In figure 5-77, the designations for the array coordinates is shown. The two coordinate planes of the array are designated by Greek letters alpha ($\alpha$) and beta ($\beta$). Each plane is displaced from the other by 90°, and, when both are 90°, they are perpendicular to the array face. When both the alpha and beta planes are 90°, their intersection forms the array reference boresight. The angle of the beam in either plane is a cosine function of the phase relationships of the elements. If all elements have the same phase (cos 90° = 1), then the beam is perpendicular to the array face in that plane.

**TRANSMIT CYCLE.**—A basic block diagram of the transmit cycle is shown in figure 5-78. The final power amplifiers (FPA) produce



OFF ARRAY WAVEGUIDE
FPA NO 1 (16 OUTPUTS)
CORRECTS PHASE
TO ARRAY NO 2
SELECTS ARRAY
FPA NO 2 (16 OUTPUTS)
CORRECTS PHASE
TRANSMIT WAVE-GUIDE ASSEMBLY
COUPLES 16 INPUTS TO 128 ARRAY MODULES
ARRAY MODULE (128)
DIVIDES SIGNAL INTO 32 OUTPUTS
SHIFTS SIGNAL PHASE
RADIATING ELEMENT (4096)
EMITS & FORMS TRANSMIT BEAM
SIGNAL PROCESSOR
ANTENNA POS PROGRAMMER
CONTROLS ANTENNA BEAM STEERING
CONTROLS PHASE SHIFT DRIVE
PHASE SHIFTER POWER SUPPLY
PROVIDES PHASE SHIFT POWER

55.443

Figure 5-78.—Transmit cycle.

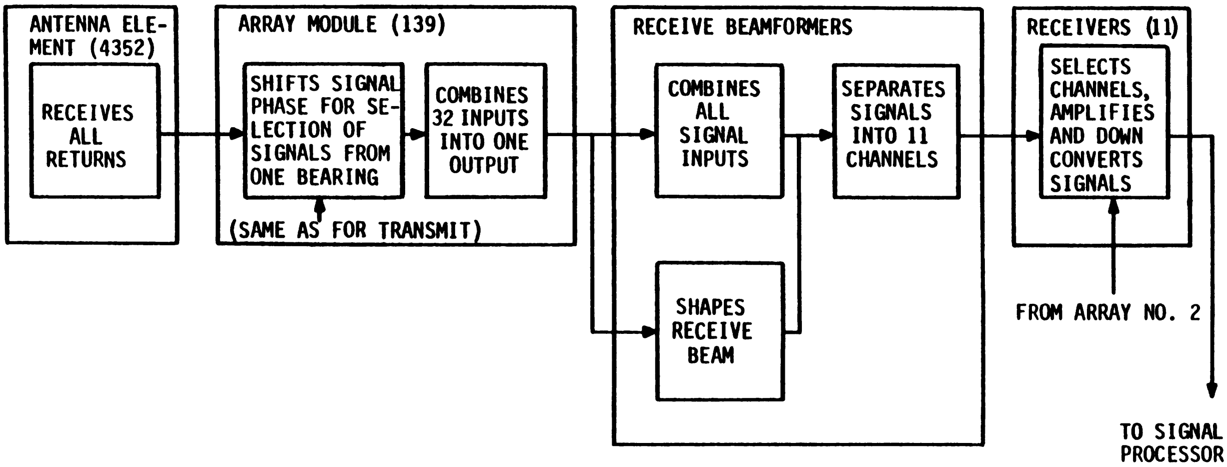
the high-power rf signal. The phase of the signal is corrected to provide the correct phase that allows the 16 rf signals to travel to one or the other of the two arrays by way of a waveguide. The 16 rf inputs to an array are divided equally between 128 array modules by magic T devices. Each array module has a coaxial power divider that couples 32 equal power and phase signals to the 32 phase shifters. Each phase shifter is programmed by the signal processor to position the beam by the phase of the signals fed to the horns.

**RECEIVE CYCLE.**—A basic block diagram of the receive cycle is shown in figure 5-79. The receive cycle is based on the monopulse principle, except the phase shifters will change the zero axis of the antenna to the desired bearing and elevation. The receive modules include receive-only sidelobe horns used for ECCM purposes. The phase shifters couple the shifted signals to the *power combiner* (divider in transmit cycle) where they are added together. The *receive beamformers* then combine the array module inputs and provide 11 channels of signals, which are sent to the receivers and signal processors. The beamformers provide the same basic function as a monopulse comparator. The sums of (Greek sigma [Σ]) of the array modules compared to the differences between top and bottom (Greek delta beta [Δβ]) and left and right (Greek delta alpha [Δα]) produce the pointing error signals when the array is used in a tracking mode. The Σ and Δ signals are produced by magic T and hybrid devices.

## SUMMARY

The microwave components covered in this chapter are the devices that connect the transmitter, receiver, and antenna together. There are other microwave components that were not covered but may be found in some radars. There are new developments that may become common components in the future. You should be aware of not only how the devices that were discussed work, but you should apply this knowledge to understanding how some of the new devices work. The main topics in this chapter are described in general terms as follows:

- Waveguides and the theory of operation. A waveguide is a hollow pipe used as a transmission line. Three basic shapes of waveguide are in common use—rectangular, circular, and elliptical. Waveguide theory is based upon the theory of electric (E) and magnetic (H) fields. Each type of waveguide has a preferred mode that the E- and H-fields will exist in and be propagated with minimum loss. This mode is called the dominant


ANTENNA ELEMENT (4352)
RECEIVES ALL RETURNS
ARRAY MODULE (139)
SHIFTS SIGNAL PHASE FOR SELECTION OF SIGNALS FROM ONE BEARING
COMBINES 32 INPUTS INTO ONE OUTPUT
(SAME AS FOR TRANSMIT)
RECEIVE BEAMFORMERS
COMBINES ALL SIGNAL INPUTS
SEPARATES SIGNALS INTO 11 CHANNELS
SHAPES RECEIVE BEAM
RECEIVERS (11)
SELECTS CHANNELS, AMPLIFIES AND DOWN CONVERTS SIGNALS
FROM ARRAY NO. 2
TO SIGNAL PROCESSOR

55.444

Figure 5-79.—Receive cycle.

mode. Electromagnetic signals can be coupled in and out of waveguides by various methods such as capacitive, inductive, and aperture coupling. Waveguides can be bent or twisted, but only within certain guidelines. Sections of waveguides are fabricated with choke joints to facilitate assembly and disassembly. Waveguides can have impedance changing devices that act as inductive or capacitive devices and even be terminated with devices that act as resistors.

- Cavity resonators. These devices can be constructed with waveguides. The cavity acts as a tuned circuit. A cavity is resonant at a particular frequency determined by the physical size of the cavity. Coupling rf into or out of a cavity is accomplished by the same method used for waveguides.

- Hybrid junctions. Three basic types of hybrid junctions are the magic T, the hybrid ring, and the short-slot hybrid junction. Hybrids are used to divide, add, or route rf energy based on its phase.

- Directional couplers. These devices are used to divide an rf signal, for sampling a signal, or routing the signal to different areas. Directional couplers can be either *one way* or *bidirectional,* meaning they can couple out energy from one direction only or from either direction.

- Ferrites. These are important microwave devices that are used as load isolators, phase shifters, variable attenuators, modulators, and switches. Ferrites are semiconductor materials that appear transparent to an electromagnetic field, but can be magnetized. Ferrites function by the interaction between the electromagnetic rf field and the magnetic field caused by the spinning electrons.

- Duplexers. They are used to isolate the transmitter from the receiver and couple the transmitter and receiver to the antenna. Various hybrid devices are used as duplexers. The duplexers use TR tube devices to perform the isolation of the receiver from the transmitter.

- Antennas. These microwave devices couple, focus, and direct the rf energy from the transmitter into space, and, in return, collect the received energy reflected from targets. Antennas establish the target line that is critical to solution of the fire control problem.

# CHAPTER 6

# COOLING AND DRY-AIR SYSTEMS

Because you operate and maintain electrical/electronic equipment, you are required to have a thorough knowledge of the various shipboard systems that support the operation of your ship's weapon system. Two such systems are cooling systems, used to cool electrical/electronic equipment, and dry-air systems, used primarily for radar waveguide pressurization.

Study the contents of this chapter carefully. The knowledge you acquire may one day help you prevent heat damage to a multimillion dollar piece of equipment. Imagine how you would feel if the damage occurred because you had not checked a temperature gage at a particular time because you were not aware of its purpose or existence. Knowledge of the equipment is one of the greatest safeguards that you can develop. Let us begin by discussing the methods for cooling electronic equipment.

## ELECTRONIC EQUIPMENT COOLING METHODS

Most electronic equipments generate sufficient heat so that some form of equipment cooling is required for normal operation. Heat is generated by various parts of the equipment because electrical energy is transformed into heat energy whenever current flows through a resistance. Excessive heat must be removed to prevent a change in the equipment operating parameters or to prevent an electrical/mechanical breakdown of individual parts.

This section on cooling systems describes some of the more common methods of heat removal from electronic equipment. It provides the basic knowledge necessary for better understanding of the major components, the operation, and the maintenance of a typical cooling system, which can be found on any fire control system. Our discussion highlights four methods of cooling. These are convection cooling, forced-air cooling, air-to-air cooling, and air-to-liquid cooling.

### CONVECTION COOLING

Cooling by the convection principle is shown in figure 6-1. As the heat of an equipment part warms the air in its vicinity, the warm air, being lighter, rises through the outlet openings. The cooler air is drawn in through the inlet openings to replace the warm air. This method is limited in its cooling effect because it relies upon the natural airflow and requires that the equipment enclosure be of open construction without air filters. To increase heat dissipation, a finned heat sink can be added to the heat-producing part, as

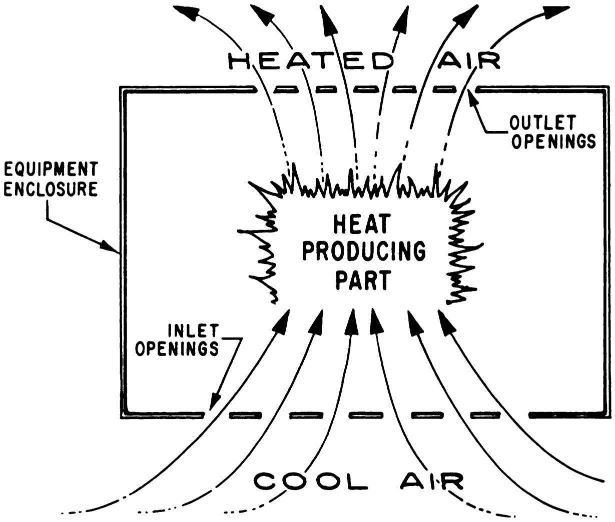


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Figure 6-1.—Convection cooling.

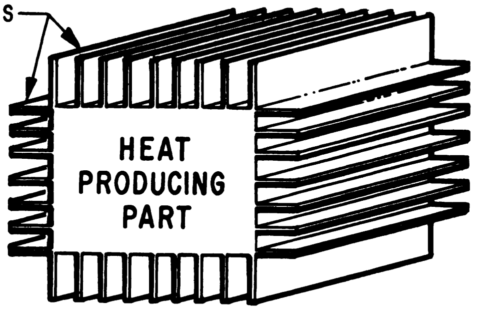

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Figure 6-2.—Finned heat sink.

shown in figure 6-2. The fins increase the effective surface area of the part, allowing more heat to be transferred to the air. For the maximum transfer of heat, the part must make contact with the heat sink. Silicone grease is usually applied between the heat source and heat sink for better thermotransfer. The heat sink must be kept free of any dirt or dust, which would act as an insulator.

## FORCED-AIR COOLING

To increase the cooling effect over that provided by convection cooling, forced-air cooling (fig. 6-3) uses a blower to provide air movement instead of the natural convection currents. Cool air is drawn into the equipment enclosure and flows past the heat producing part, picking up the heat. The air is then exhausted out of the equipment. An air filter is provided at the air inlet to remove dust and dirt that otherwise would settle on the internal parts of the equipment. The air filter must be kept clean according to the equipment's maintenance requirements. This will ensure maximum air movement and cooling.

In some equipment, a honeycomb rf interference filter is installed on both input and outlet to prevent stray rf from entering or leaving the equipment cabinet. This filter can also collect dirt that can reduce the airflow.

Failure of a bearing in the blower motor is not an uncommon problem. A replacement of both blower motor bearings or blower assembly is warranted at the first sign of abnormal operation, such as excessive noise or vibration. It is better to replace the bearings than to risk damage to the equipment that the blower motor is designed to protect.

## AIR-TO-AIR COOLING

Some units of electronic equipment are hermetically sealed to prevent the entrance of moisture. For equipment of this type, an air-to-air heat exchanger (fig. 6-4) is used to prevent the air inside the equipment enclosure from mixing with the outside air and still allow cooling to take place. Air moving past the heat producing part absorbs heat and is forced through a heat exchanger by an internal blower. The heat in the internal air is absorbed by the heat exchanger. The cooled internal air is then returned to the equipment interior to continue the cycle.

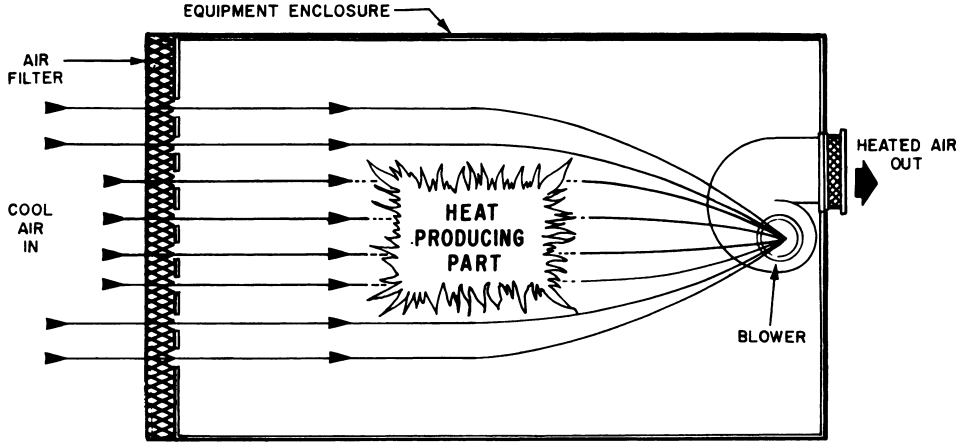

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Figure 6-3.—Forced-air cooling.

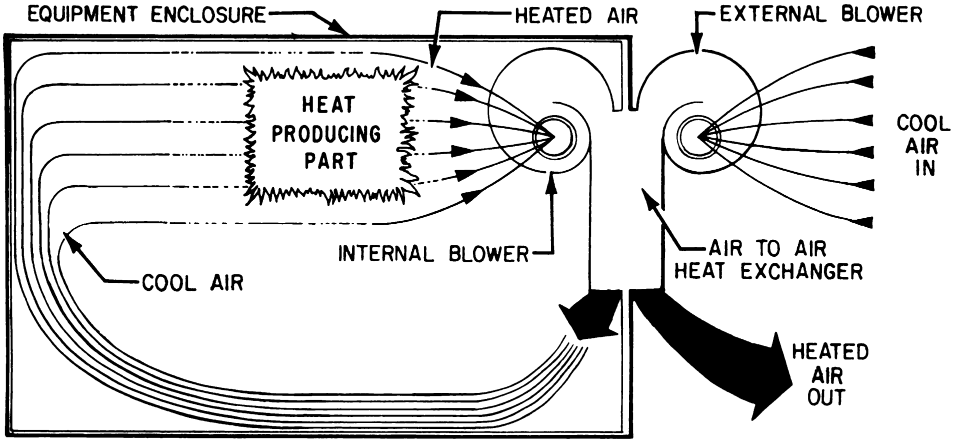

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Figure 6-4.—Air-to-air cooling.

Heat is removed from the heat exchanger by forcing cool outside air through the heat exchanger by an external blower. There is no physical contact between the internal and external air. In some applications, the internal air is replaced by an inert gas such as nitrogen to prevent oxidation.

## AIR-TO-LIQUID COOLING

A more efficient heat transfer is possible by replacing the air-to-air heat exchanger with an air-to-liquid heat exchanger (fig. 6-5). In this method, the internal air is also circulated past the heat producing part and through a heat exchanger, but the heat is removed from the heat exchanger by a liquid coolant circulating through the heat exchanger.

Air-to-liquid cooling systems usually employ built-in safety devices to shut down the equipment to prevent overheating. The overheating could be caused by low or no liquid flow, liquid too hot, an inoperative circulating fan, or reduced heat exchanger efficiency because of improper maintenance.

This type of cooling system is normally found on large equipment installations where a large amount of heat is developed. Many radar transmitters, for example, require cooling of this type. The other types that we have discussed

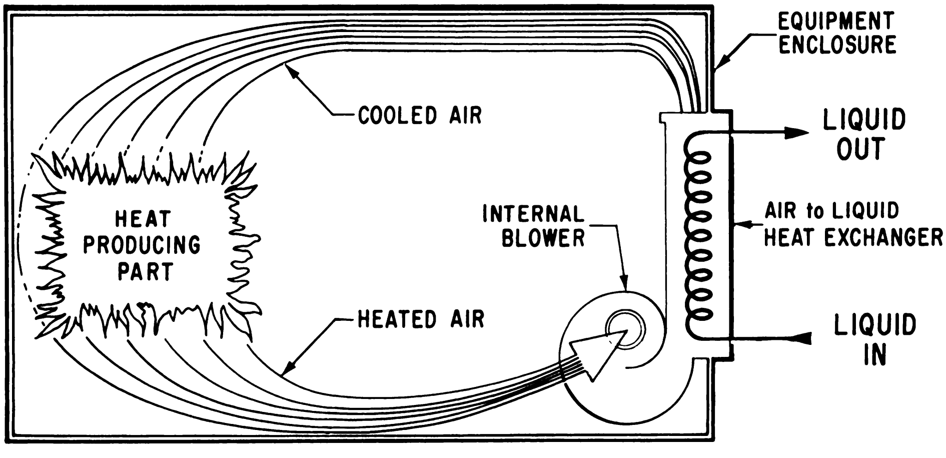

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Figure 6-5.—Air-to-liquid cooling.

would not be able to dissipate the heat that a high-powered radar transmitter develops. A disadvantage of this type of cooling system is that they are larger and more complex. However, for this reason and because they are a part of the more complex systems, we describe the typical liquid cooling system used aboard ship. In this way, you will be given a better understanding of the function of individual components within a system and the basic maintenance required to maintain the system to a high state of readiness.

## LIQUID COOLING

Cooling systems are essential to the satisfactory operation of a shipboard weapons system. In fact, some form of cooling is required for all shipboard electronic equipment. As we have indicated, liquid cooling is especially efficient for the transfer of large amounts of heat. To maintain cooling systems, you must have a broad understanding of the different types of liquid cooling systems that you are involved with.

A typical liquid cooling system is composed of two basic coolant systems. First, there is the primary system. It provides the initial source of cooling water that can be either seawater or chilled water from the ships air-conditioning plant, or a combination of both. Next, the secondary system transfers the heat load from the electronic equipment to the primary system. The coolant normally used in the secondary system is distilled water. This distilled water is *ultrapure* and is maintained in that state by a demineralizer. In some secondary systems, ethylene glycol is added to the water to prevent freezing when the system is exposed to freezing weather.

### TYPES OF LIQUID COOLING SYSTEMS

In the U.S. Navy, there are three basic configurations of liquid cooling systems, and conceivably you could be involved with all three. The type or types with which you may be involved, depends upon the number and types of electronic equipment to be cooled. The three types of systems are as follows:

- Type I—Seawater/distilled water (SW/DW) heat exchanger with SW/DW heat exchanger standby

- Type II—SW/DW heat exchanger with a chilled water/distilled water (CW/DW) heat exchanger standby

- Type III—CW/DW heat exchanger with a CW/DW heat exchanger standby

The specifications for the type of system installed on your equipment will depend upon the operational requirements of the equipment. Some electronic equipments require very close regulation of the temperature of the distilled water; whereas, others do not.

Type I (SW/DW) systems are used for electronic system installations that can be operated satisfactorily with seawater temperature as high as 95 °F. This should result in a distilled water supply temperature to the electronics of approximately 104 °F. Type II (SW/DW, CW/DW) systems are used in installations that cannot accept a DW temperature higher than 90 °F. Type III (CW/DW) systems are used in installations where the temperature range is critical. They require close regulation of the DW coolant to maintain temperatures between established limits. For example, the temperature limits might be 70° and 76 °F. As you can see, Type III systems are used where tighter control is required.

Liquid cooling systems are composed of piping, valves, regulators, heat exchangers, strainers, circulating pumps, expansion tanks, gages, and a demineralizer. In some systems, there are specialized components to monitor cooling water to the electronic equipment. Let's examine this in greater detail by discussing the operation of the three types of liquid cooling systems. Before doing so, however, let's look at the systems in terms of primary and secondary systems.

### PRIMARY COOLING SYSTEM

The cooling water for the primary cooling system is either seawater or chilled water. The seawater, obviously, is from the sea and the chilled water is from the ship's air-conditioning plant. Figures 6-6, 6-7, and 6-8 show the basic arrangements of systems using seawater and chilled water.

In figure 6-6, seawater from a sea connection is pumped by a seawater circulating pump in one of the ship's engineering spaces through a duplex strainer to remove all debris and then through the tubes of a heat exchanger. Finally, it is discharged back into the sea at an overboard discharge. The seawater system shown in figure 6-6 is a

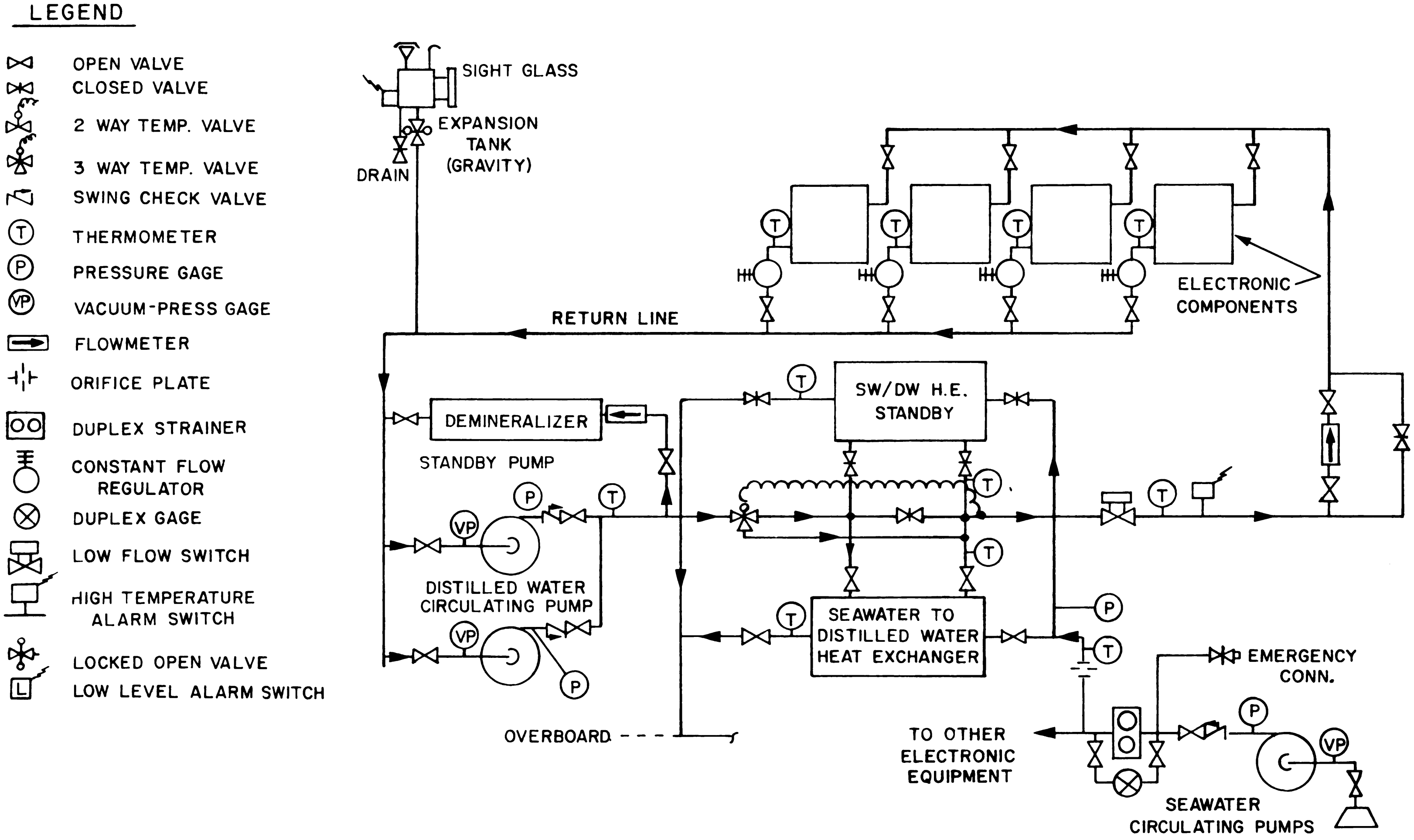

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Figure 6-6.—Type I liquid-cooling system.

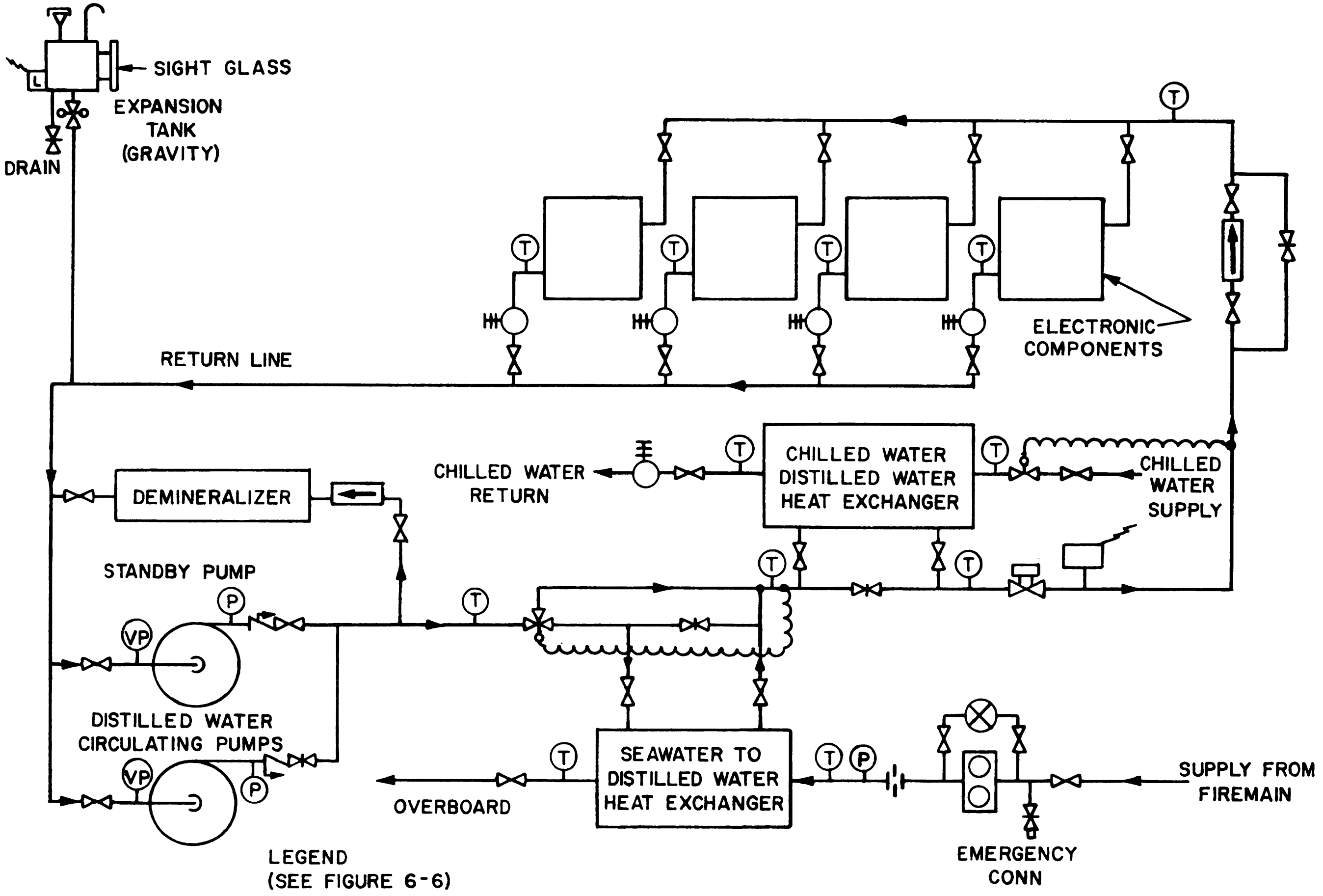

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Figure 6-7.—Type II liquid-cooling system.

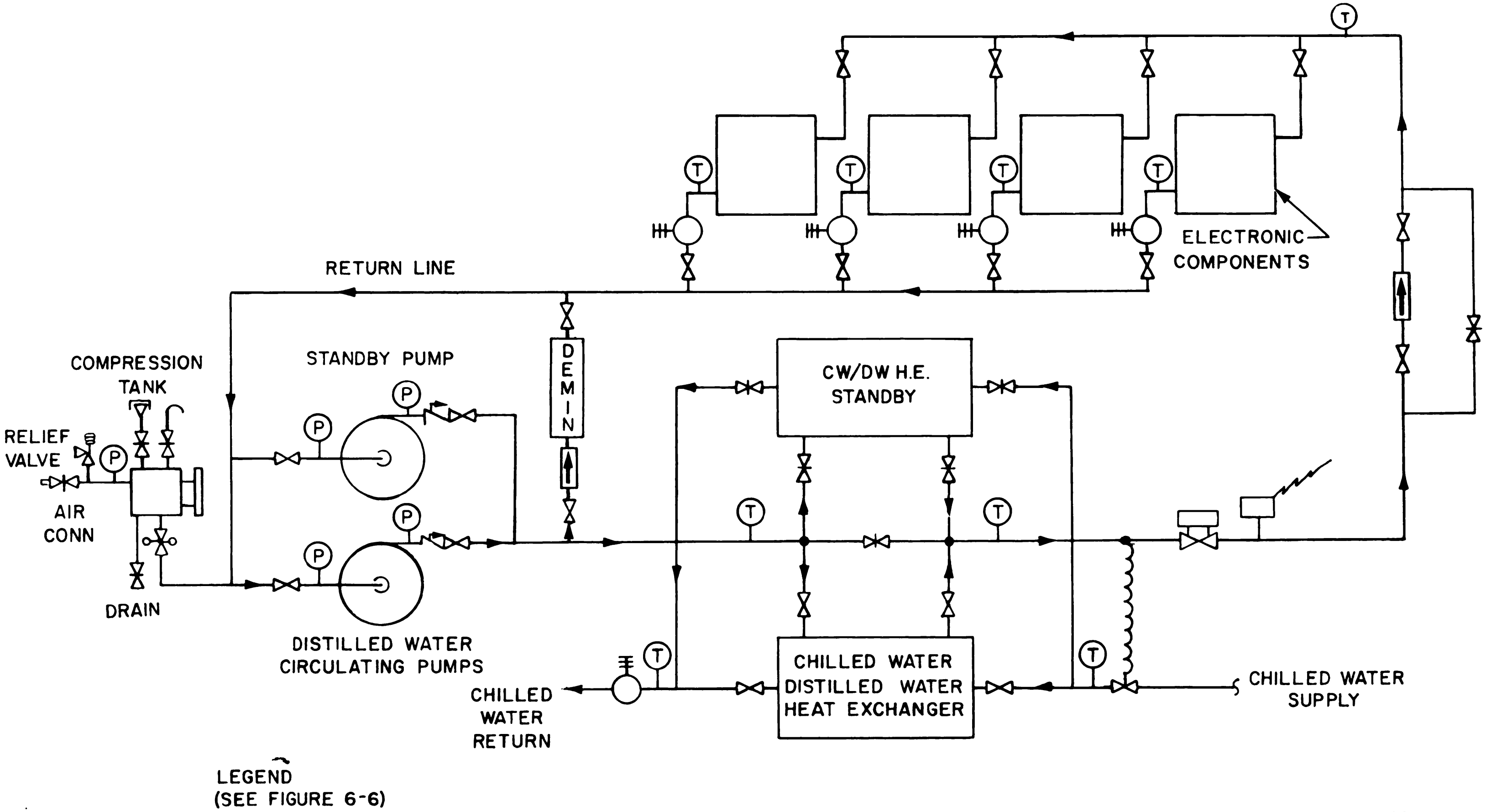

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Figure 6-8.—Type III liquid-cooling system.

multiple-branch system. As such, it supplies a number of heat exchangers for other electronic equipment. To regulate the proper amount of seawater to each cooling system, an orifice plate is installed in the line between each heat exchanger and the duplex strainer. The heat exchangers are referred to as seawater-to-distilled-water heat exchangers.

Another means of providing seawater is through the ship's firemain, as shown in figure 6-7. The seawater is taken from the firemain through a duplex strainer and a flow regulator (orifice plate) to and through the heat exchanger. It is then discharged overboard. The connection to the firemain is permanent.

The ship's fire pump, not shown in figure 6-7, is used to pump seawater into the firemain. The fire pump is similar in design to the previously mentioned seawater circulating pump, except it has a much larger capacity.

Another means of getting seawater as a primary coolant is by an emergency connection (figs. 6-6 and 6-7). This method is used if the normal seawater supply is lost. The connection is usually by means of a 1 1/2-inch fire hose. The emergency supply comes from an alternate portion of the ship's firemain or a portable pump rigged by the ship's damage control party. The portable emergency hose is normally stored in the liquid coolant machinery room.

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Seawater systems are referred to as open-loop or one-pass systems because the seawater flows through the system only once.

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In figures 6-7 and 6-8, chilled water is taken from the supply main of the air-conditioning, chilled-water systems. The chilled water is used as a backup source of cooling water for the primary cooling system shown in figure 6-7, and as a normal and backup source in the system shown in figure 6-8. The chilled water flows through the tubes of the heat exchanger (chilled water to distilled water), a flow regulator, and back to the chilled-water system. A temperature regulating valve at the inlet of the heat exchanger regulates the flow of chilled water through the heat exchanger to maintain the required water temperature in the secondary system (distilled water). The ship's air-conditioning, chilled-water circulating pump is used to pump the chilled water through the heat exchanger. The chilled-water system is a closed-loop water system because the water is recirculated. It must be kept tight and free from leaks to assure satisfactory operation.

## SECONDARY COOLING SYSTEM

The secondary cooling system is designed to transfer heat from the electronic equipment being cooled to the primary cooling system. This system is usually comprised of a distilled-water circulating pump, a compression or gravity-feed expansion tank, the electronic equipment being cooled, a demineralizer, a temperature control valve, monitoring equipment with its associated alarms, and the heat exchanger, which is shared with the primary system. The secondary system is a closed-loop water system, as compared to the seawater system, which is a one-pass or open-loop system.

## TYPE I COOLING SYSTEM

We are now ready for a more detailed look at the types of cooling systems. Let's begin by looking at the Type I system. Starting with the distilled water pumps (fig. 6-6), distilled water under pressure flows to the temperature regulating valve. The temperature regulating valve is installed to partially bypass distilled water around the sea-water-to-distilled-water heat exchanger so that a constant water temperature can be supplied to the electronic equipment. As the temperature in the distilled water increases, more water is directed to the heat exchanger and less to the bypass line. This maintains the output water temperature constant. The standby heat exchanger is usually of the same design and is used when the *on-line* heat exchanger is inoperable or is having maintenance performed on it. The size of the heat exchanger is designed to handle the full cooling load of the electronic equipment plus a 20 percent margin. From the heat exchanger, the water then goes through various monitoring devices, which check the water temperature and flow. These two things depend upon the requirements of the electronic equipment being cooled. After the water moves through the equipment, it is drawn back to the pump on the suction side. In this way, a continuous flow of coolant is maintained in a closed-loop system.

An expansion tank is provided in the distilled water system to compensate for changes in the coolant volume, and to provide a source of makeup water in the event of a secondary system leak. When the expansion tank is located above the highest point in the secondary system and vented to the atmosphere, it is called a gravity tank. If it is below the highest point in the secondary cooling system, then it is called a compression tank, because it requires an air charge on the tank for proper operation.

The demineralizer is designed to remove dissolved metals, carbon dioxide, and oxygen. In addition, a submicron filter (submicron meaning less than one millionth of a meter) is installed at the output of the demineralizer to prevent the carry-over of chemicals into the system and to remove existing solids.

### TYPE II COOLING SYSTEM

The secondary system of the Type II cooling system (fig. 6-7) is similar to the Type I secondary coolant system and uses many of the same components. The major difference is in the operation of the CW/DW heat exchanger. The secondary coolant is in series with the SW/DW heat exchanger and automatically supplements the cooling operation when the SW/DW heat exchanger is unable to lower the temperature of the distilled water to the normal operating temperature. The CW/DW temperature regulating valve allows more chilled water to flow in the primary cooling system to the CW/DW heat exchanger. This causes the temperature in the secondary system to go down. Normally, this action only occurs in the event of high seawater temperatures encountered in tropic waters. The CW/DW heat exchanger is also used in the event of an SW/DW heat exchanger malfunction.

### TYPE III COOLING SYSTEM

The Type III secondary cooling system (fig. 6-8) also operates in a similar manner to the Type I system. The major difference is in the way that the temperature of the secondary coolant is regulated. A three-way temperature regulating valve is not used. A two-way temperature regulating valve is used in the primary cooling loop to regulate the temperature of the secondary loop.

The duplicate CW/DW heat exchanger is installed parallel to the first heat exchanger and is used as a standby heat exchanger. In the event that a malfunction occurs requiring the first heat exchanger to be removed from service, the standby exchanger can be put into service by manipulating the isolation valves associated with the two heat exchangers.

## COOLING SYSTEM COMPONENTS

You should be able to identify and describe the operation of the individual components of a typical cooling system. This will help you to perform the required system maintenance and trouble isolation. You should never neglect the cooling system, because it will quickly deteriorate to a point where only extreme and costly maintenance will restore the system to its proper performance.

### HEAT EXCHANGERS

In the liquid coolant heat exchangers, heat that has been absorbed by distilled water flowing through the electronic components is transferred to the primary cooling system, which contains either seawater or chilled water from an air-conditioning plant. In both cases (figs. 6-9 and 6-10), the heat exchangers are of the shell and tube type in which the secondary coolant (distilled water (DW)) flows through the shell, while the primary coolant (seawater (SW) or chilled water (CW)) flows through the tubes.

A single-pass counterflow heat exchanger (fig. 6-9) is more efficient than the double-pass heat exchanger, because there is a more uniform gradient of temperature difference between the two fluids. In figure 6-9, the primary coolant (SW/CW) flows through the tubes in the opposite direction to the flow of the secondary coolant (DW). Heat transfer occurs when the seawater flows through the tubes; extracting heat from the distilled water flowing through the shell side of the heat exchanger. The distilled water is directed by baffles to flow back and forth across the tubes as it progresses along the inside of the shell from inlet to outlet. In figure 6-9, the preferred method of double-tube sheet construction is shown. Single-tube sheet construction is shown in figure 6-10.

Double-tube sheets are used at both ends of a tube bundle. A void space between the sheets prevents contamination of the distilled water and permits the monitoring of water loss due to tube leakage. You should be on the lookout to detect leakage at the "telltale drains," which indicates a failure of a tube joint. The type of water leaking out indicates whether the failure is in the primary or the secondary system. The telltale drains should never be plugged or capped off. A leak in one of the tubes shows up as a loss of water in the secondary side of the liquid coolant system, because it operates at a higher pressure than the

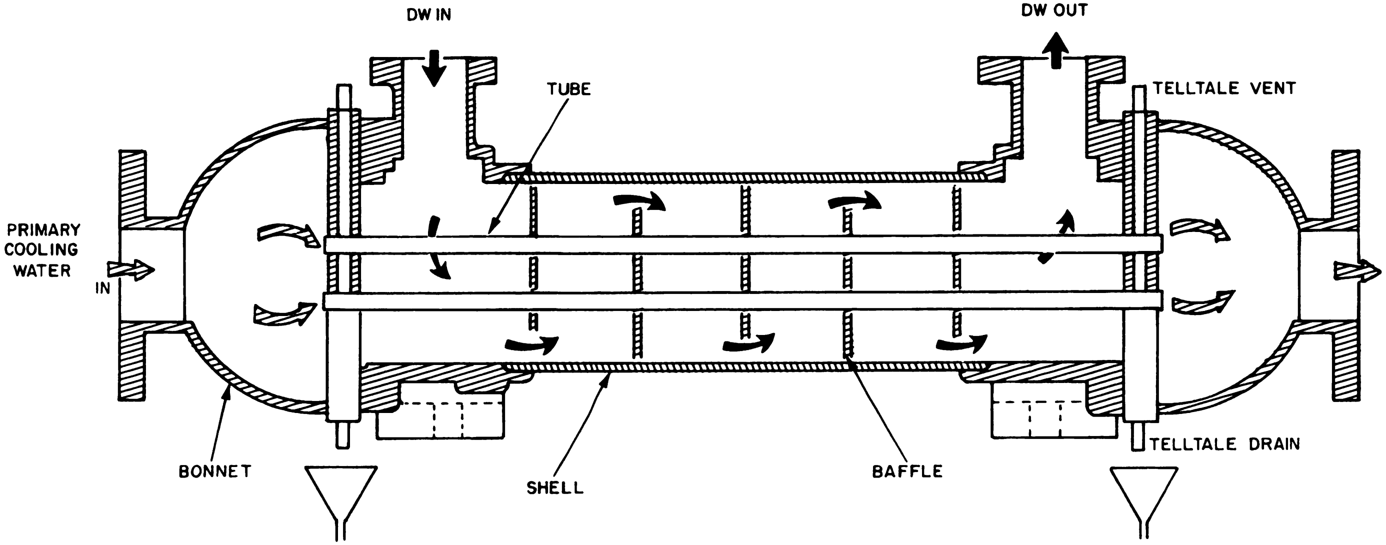

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Figure 6-9.—Single-pass SW/DW heat exchanger with double tube sheets.

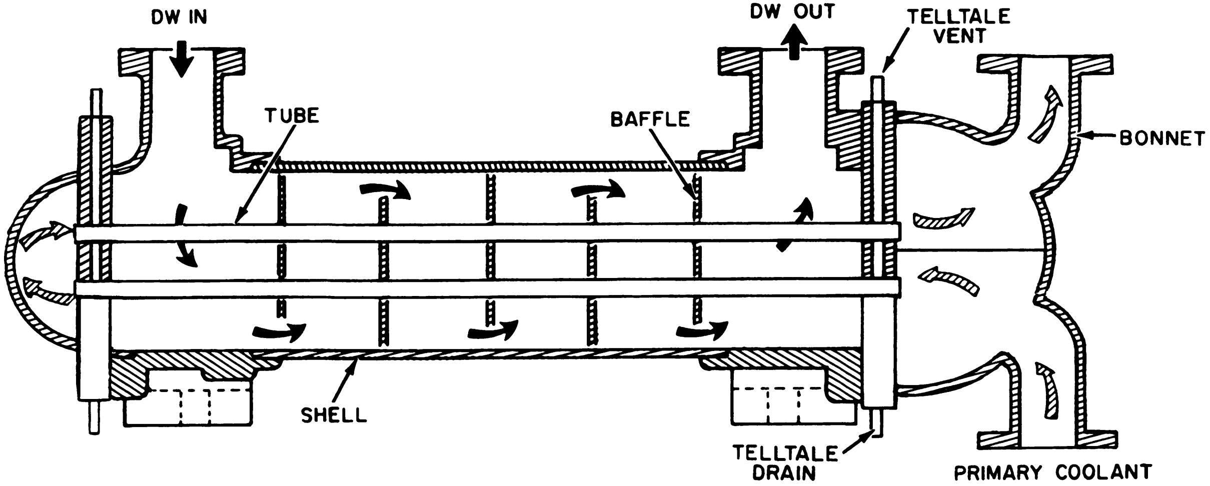

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Figure 6-10.—Two-pass SW/DW heat exchanger with single tube sheets.

primary side. This is intentional. This ensures that the distilled water is not contaminated with seawater when a leak develops in a heat exchanger.

A double-pass heat exchanger is generally used when there is limitation on the installation of the heat exchanger. This type of heat exchanger is less efficient than a single-pass exchanger and is subject to internal undetectable leakage across the flow divider in the inlet-outlet water box.

It is to your advantage to maintain a log on the performance of the heat exchangers installed in the cooling systems with which you are involved. By recording the operating characteristics, you will have the data you will need to later analyze the performance of the heat exchanger. The performance is monitored by observing the temperature gradient (ΔT) between the inlets and outlets of the two fluids. The overall effectiveness of a heat exchanger is determined by comparing its primary inlet temperature to its secondary outlet temperature. For example, with no change in the primary or secondary flow and if the heat transfer capacity of the heat exchanger drops, the ΔT will increase. By comparing the ΔT readings taken periodically with the clean heat exchanger ΔT readings, you can detect the deterioration of a heat exchanger because of fouling. By maintaining a record of both input and output pressure gradient (ΔP), you will be able to determine which side of the heat exchanger is fouled.

Heat exchangers must periodically be cleaned. The secondary section (distilled water) is cleaned by circulating chemicals through the secondary cooling system to remove any buildup of scale deposits, which accumulate on the surface of the tubes. The procedure for routine cleaning of the primary section of the heat exchanger is to first secure the sea connections to prevent flooding. In some cases, an inspection port in the water box can be opened to remove any foreign matter lodged inside and against the tubes. If you are unable to get at the ends of the heat exchanger to remove the water boxes, then you must remove the heat exchanger from its location and place it on the deck or a suitable work surface. Mark each unit removed so that it can be positioned in its proper place during reassembly. With the water boxes removed, an air lance should be passed through each tube and the passages washed out. Where severe fouling exists, a water lance should be pushed through each tube to remove foreign matter attached to the tube walls. Where *extreme* fouling exists, special cleaning equipment operated by personnel skilled in their use is required. The ship's engineering officer is the best person qualified to determine which procedure to use and whether the job can be performed aboard ship or if it must be transferred to a repair facility. You should take precautions to ensure that tools, such as screwdrivers and wire brushes, are not used in such a way that they may scratch or mar the tube surfaces.

Over a period of time, electrolysis, which results because of dissimilar metals in the cooling system, will slowly dissolve the insides of various components in the primary seawater cooling system. (Electrolysis is not a problem in chilled water systems to the extent that it is in seawater systems.) The type of metal used in the fabrication of the heat exchanger tubes is the deciding factor as to the use of zincs. Zincs are disks, rods, bars, or plates made of zinc metal that are installed inside the heat exchanger's water boxes. When zincs are installed, the electrolytic action is concentrated on the zinc and not on the metal of the heat exchanger tubes. As electrolysis dissolves the zincs instead of the heat exchanger tubes, they should be replaced. (The purity of distilled water inhibits electrolysis in the secondary system.)

In an older cooling system, you should be on the lookout for thin pipes in the seawater side of the cooling system. You can check for bad pipes by gently tapping the empty pipes with the ball of a ball-peen hammer. A bad piece of pipe will make a dull sound and dimple as it is struck lightly.

The heat exchangers in the distilled water cooling systems that cool electronic equipment are either liquid-to-air or coolant-jacket type of heat exchangers. The liquid-to-air heat exchangers are mounted inside cabinets containing the heat-producing electronic components. A cabinet fan circulates the air across the heat exchanger and to the heat source in an airtight circuit. In the coolant-jacket type of heat exchangers, the distilled water is circulated through an integral water jacket in a large heat-producing component such as a power-amplifier tube, a plate transformer, or load isolators. Vent and drain connections are provided to permit the venting of trapped air and the draining of water. Temperature gages may be provided in the inlet and outlet piping to check performance of the heat exchanger. Label plates indicate the water flow direction through each cabinet. Flow regulators (orifice plate or constant-flow device) usually provide a constant flow of coolant to the individual component, cabinet, or bay of electronic equipment to be cooled. On critical electronic components that would be damaged without coolant to remove the heat, coolant flow and temperature switches monitor the coolant.

## EXPANSION TANK

The expansion tank serves a threefold purpose in a liquid cooling system. First, it maintains a positive pressure required on the circulating pump inlet for proper operation of the circulating pump. Second, the expansion tank compensates for changes in the coolant volume because of temperature changes. Third, it vents air from the system and provides a source of makeup coolant to compensate for minor losses because of leakage or losses that occur during the replacement of radar equipment served by the system. The tank may be either a gravity tank or a pressurized tank.

When an expansion tank is used as a gravity tank (fig. 6-11), it is located above the highest point in the distilled water system. This provides sufficient pressure to the suction side of the circulating pump. This also ensures a flow of water from the tank into the system when makeup water is required. The tank is provided with a sight glass to check the level of water in the tank. The sight glass should normally show the tank to be two-thirds to four-fifths full. The glass should be redlined at four-fifths of the tank capacity. A vent pipe is located on the top of the tank to prevent air pressure from building up in the system. A valve and funnel connection with cap are located on the top of the tank to provide a means for filling the system with distilled water. A low-level alarm switch is usually set at 20 percent of tank capacity. When the fluid level in the tank lowers to 20 percent of the full level, visual and audible alarms actuate at the alarm switchboard to warn personnel when the system is low on distilled water. If the tank should run out of water, then air is drawn into the system, which results in increased corrective maintenance on the system to remove the trapped air or possible pump damage and/or failure of high power transmitter components.

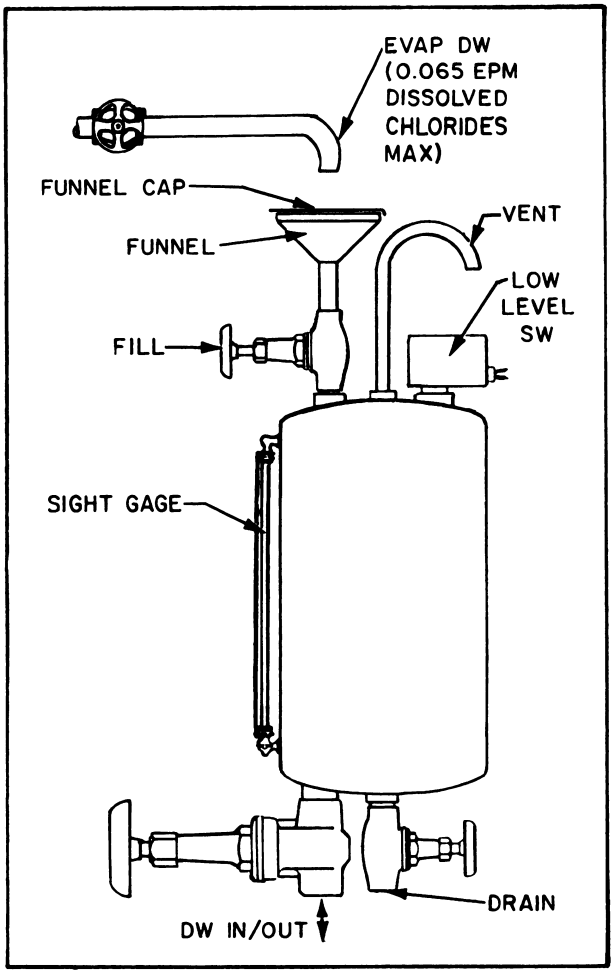

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Figure 6-11.—Gravity expansion tank.

The pressurized expansion tank (fig. 6-12) is normally located near the circulating pump suction in the return main of the secondary liquid cooling system. The pressurized tank is airtight and is charged with compressed air to an appropriate pressure from the ship's low-pressure air system. In some systems, a hose is used to pressurize the tank through a quick disconnect or Schrader valve. In other systems, a permanent pipe installation is connected to the expansion tank through a pressure-relief valve and an air shutoff valve. The ship's low-pressure air system is used to charge the pressure tank, and then it is secured to prevent a possible floodback of coolant into the low-pressure air system. The relief

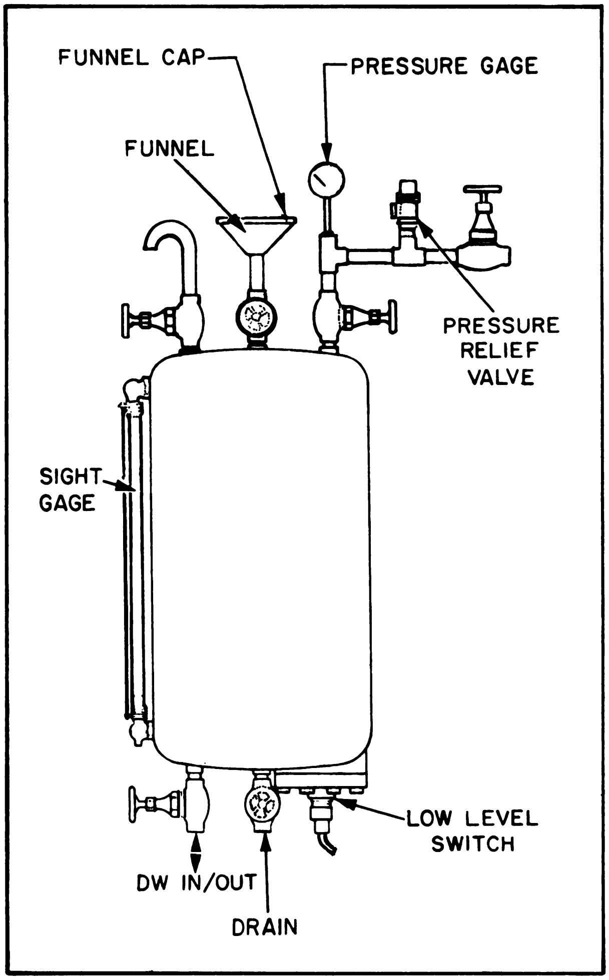

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**Figure 6-12.—Pressure expansion tank.**

valve is provided to protect the tank and distilled water system from being overpressurized. The sight glass and the low-level alarm switch function the same as those on the gravity expansion tank.

In both types of expansion tanks, the bottom of the tank is connected by piping to the return main of the secondary cooling system (fig. 6-6). Changes in coolant volume causes the coolant to flow into or out of the reservoir as necessary to maintain a stable, liquid coolant, return-line pressure.

Makeup water (distilled water) is added to the expansion tank through the funnel located on the top of the tank (fig. 6-11 and 6-12). A funnel cap is provided for the funnel to prevent dirt from entering the system through the funnel. Whenever you fill the pressurized expansion tank, you have to first isolate the tank from the cooling system and the air supply, then vent the air pressure off through the vent pipe located at the top of the tank. The makeup water can be obtained directly from the ship's evaporators and preferably when the ship is making boiler feed water, because the water is double distilled. At NO time should potable (drinking) water or treated boiler feedwater be used in any electronic cooling systems. After the water is drawn from the ships evaporators, it should be transported using only a clean capped container. You should take a sample of the water from the containers and have it tested for chloride by the ship's water test facility before any of the water is used in the cooling system. The maximum permissable level of chloride is .065 epm (equivalent parts per million). The supply system provides an alternate source of makeup water.

The expansion-tank sight glass is your best indication of a coolant leak in the secondary cooling system. When the system uses excessive makeup water, you should inspect the whole secondary system, including the telltale drains on the heat exchanger, to locate the source of the leak. A small drip can amount to several gallons of water a day. On the pressurized expansion tank, a very small air leak indicated by a pressure drop on a tank gage can be located by brushing on a leak detector (a thick, clear, soapy liquid such as concentrated liquid dishwasher soap) over the suspected area of the leak. The escaping air causes bubbles to form in the leak detector.

## SEAWATER STRAINERS

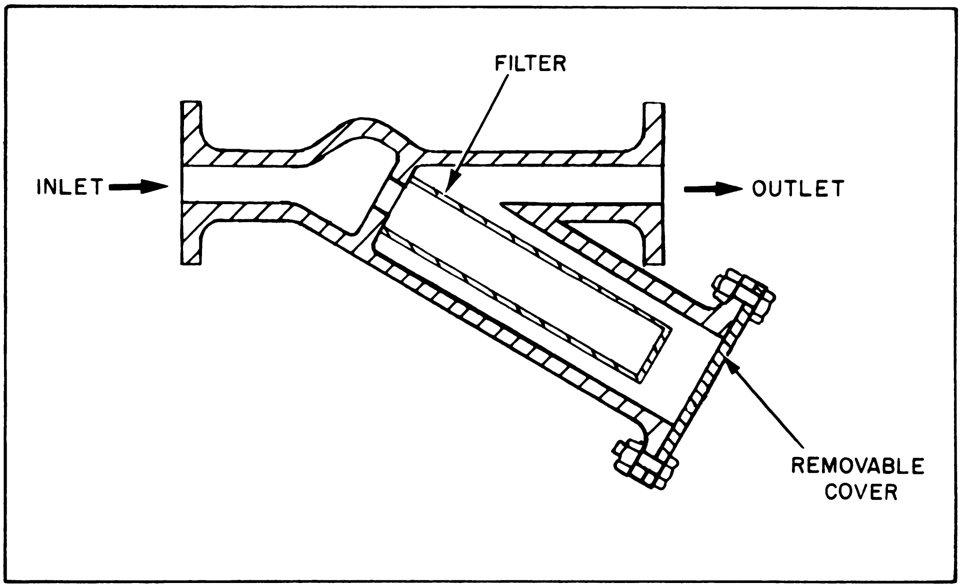
Strainers are used in the seawater cooling system to remove debris and sea life, which could clog the pressure and flow control device (orifice) and/or the tubes of the heat exchanger. The two types of in-line seawater strainers most commonly used in weapons cooling systems are the simplex (single) and duplex (double) basket strainers.

The simplex basket strainer (fig. 6-13) consists of a Y-pattern body housing a wire mesh basket. Some simplex strainers have a small drain on the cover to allow you to drain the water off before removing the cover. The basket is removed periodically for cleaning and inspected for deterioration. This type of strainer requires that the seawater be secured before you clean the basket.

The duplex strainer (fig. 6-14) consists of two removable baskets located in parallel at the seawater inlet. Seawater flows into the top of one basket and out through the perforated sides to the outlet. This arrangement allows maintenance to be performed on one basket while the system is in operation. A selector valve is arranged so that with the handle in one position, seawater flows through one of the baskets, leaving the other basket accessible for removal and cleaning. By switching the valve handle to the alternate position, flow is shifted over to the other basket.

A duplex pressure gage monitors the differential pressure between the inlet and outlet ports of the duplex strainer. The purpose of the duplex gage is to provide a visual indication of a clogged strainer basket. To correctly use the gage, it should be marked when the basket is clean. When the basket is clogged, the pressure reading is usually 5 to 10 psi above the clean-basket reading. If the pressure drop is less than the clean-basket reading, a check should be made for a damaged basket or missing basket.

The basket handle (spring handle) acts as a spring-load to seat and hold the basket in the housing. A damaged spring handle will permit debris to bypass the strainer basket and clog the heat exchanger tubes. In some cases, the basket may spin inside the duplex strainer and physically wear away the basket seat and/or the side of the duplex strainer. The duplex strainer would then have to be removed for extensive repairs, possibly off ship. New or replacement baskets should always be checked for proper spring-handle pressure against the top of the basket cover. You should use only the correct gasket material for the basket covers, as specified in the



55.328

Figure 6-13.—Seawater simplex strainer.

COSAL. Inferior material can stretch and be forced out from under the cover, and then seawater could spray out and possibly flood the space.

## TEMPERATURE REGULATING VALVES

The temperature regulating valve regulates the amount of cooling water flowing through or bypassing a heat exchanger to maintain a desired temperature of distilled water going to the electronic equipment. Temperature regulating is usually provided by either a three-way or a two-way temperature regulating valve or a combination of both valves, as shown in figure 6-7. The three-way valve is used where seawater is the primary cooling medium in the heat exchanger, and the two-way valve is used where chilled water is the primary cooling medium.

### Three-way Temperature Regulating Valve

The three-way regulating valve (fig. 6-7) is installed so that the incoming distilled water to the valve can be directed to the heat exchanger or caused to bypass the heat exchanger. More accurately, the distilled water is proportioned between these two paths. The valve senses the temperature of the distilled water downstream of the junction between the heat exchanger outlet and the bypass and then proportions the two flows to obtain the desired temperature. The three-way temperature regulating valve's range of operation is within ±5 degrees of the setting on the valve.

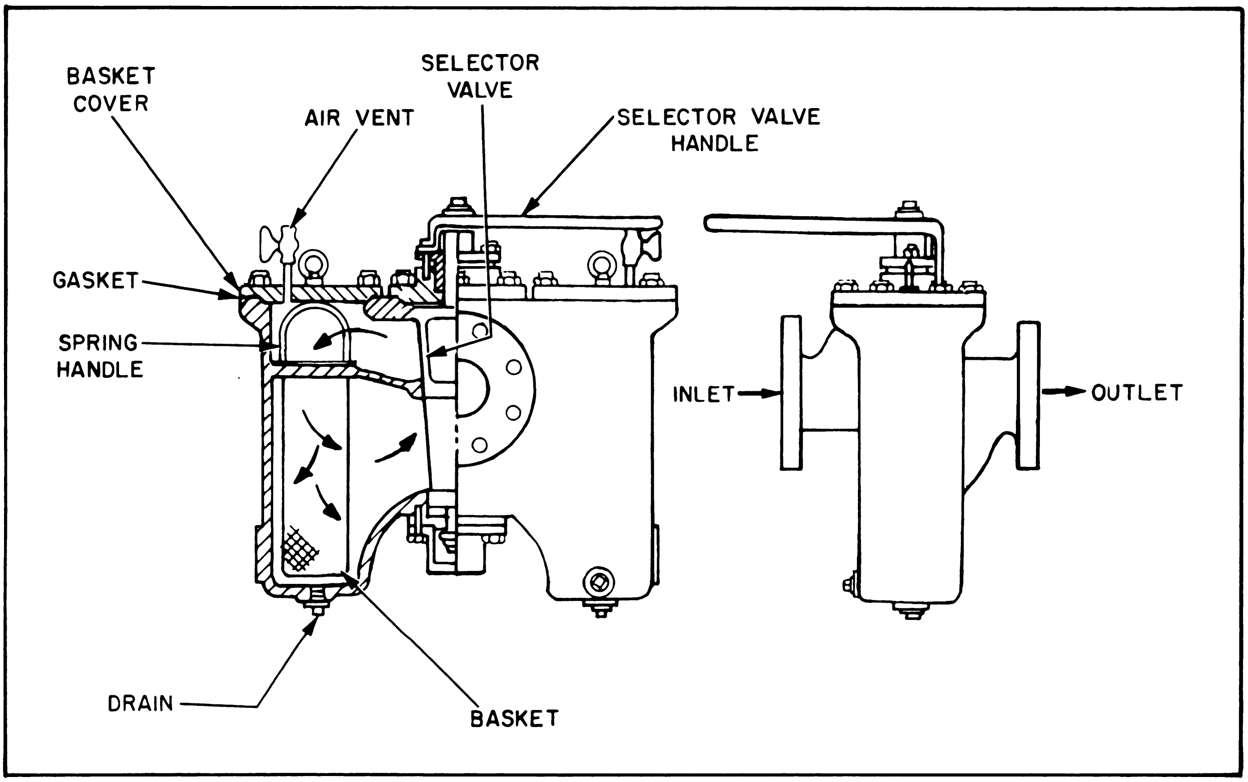


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Figure 6-14.—Seawater duplex strainer.

Refer to figure 6-15 for the following description of the operation of a three-way regulating valve. The bulb contains a volatile liquid that vaporizes and expands when heated. The pressure generated in the bulb is a function of the temperature around it. This pressure is transmitted through the capillary tubing to the flexible bellows, which are loaded by the spring. Both bellows and spring rest on the end of the valve stem. Expansion or contraction of the bellows causes movement of the stem and the piston in the valve body. The flow of the liquid entering the valve at port A is proportioned between ports B and C in the proper ratio to maintain the mixed flow temperature at the valve's *set point*. Total flow through the valve remains constant. Movement of the bellows is opposed by the spring, which is provided with a

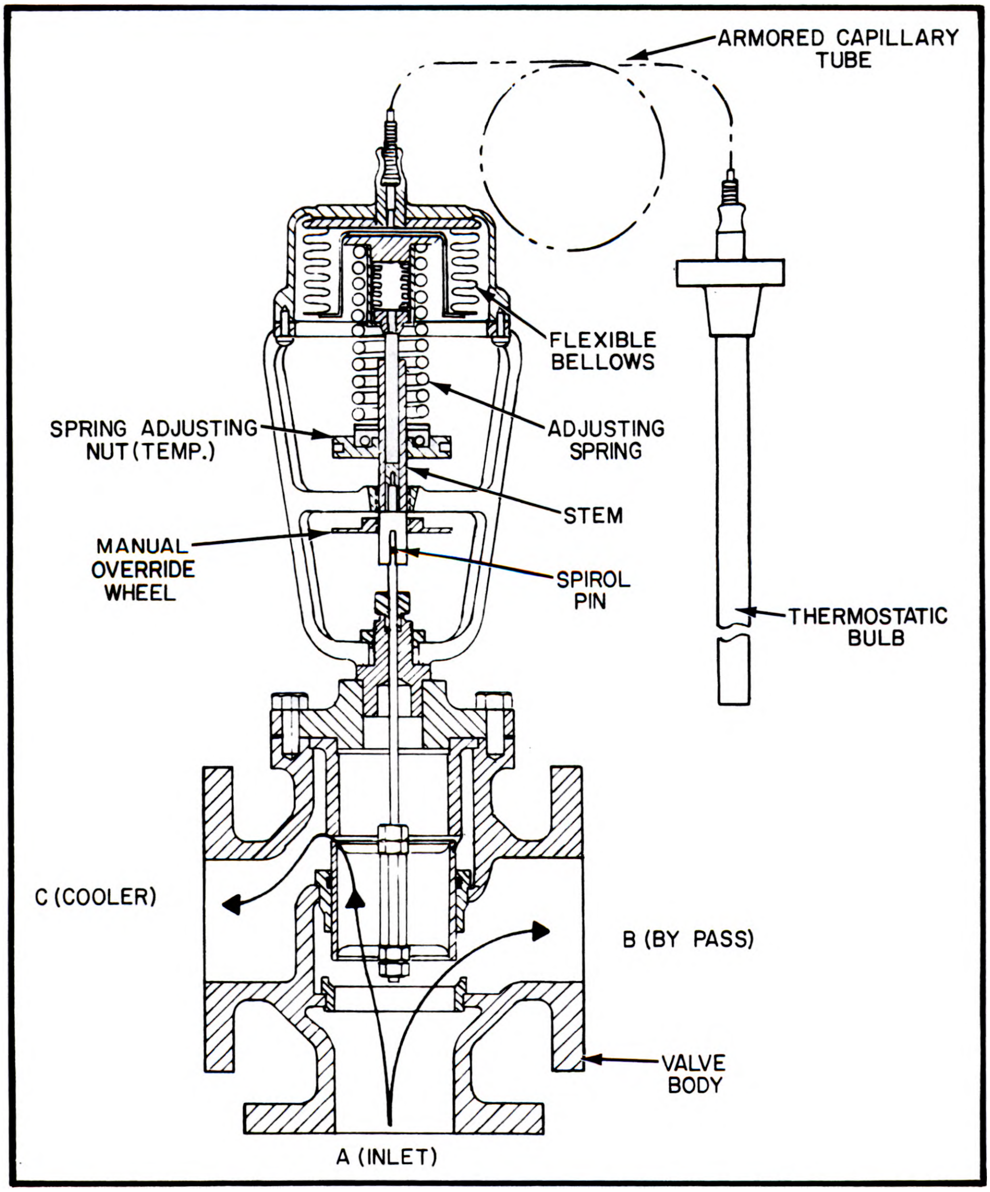

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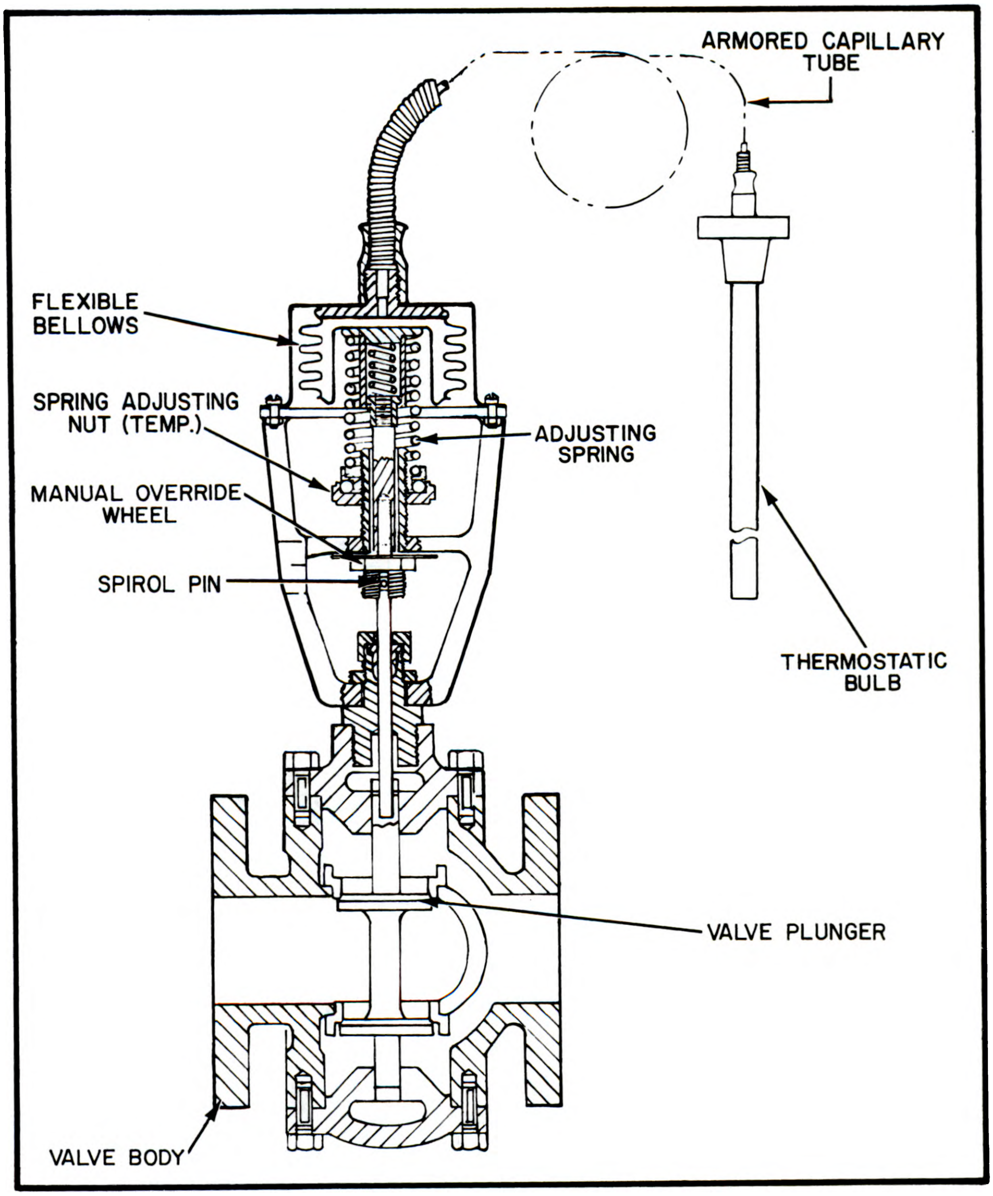
Figure 6-15.—Three-way temperature regulating valve.

means to adjust the operating temperature by the spring-tension adjustment wheel. A drop in temperature at the thermostatic bulb reduces the pressure in the thermostatic assembly, causing it to exert less force, resulting in an upward movement of the stem because of the force of the spring. As the stem is connected to the piston, the piston also moves upward, enabling more liquid to pass from the bottom inlet through the right outlet (bypass) side and, at the same time, restricting flow through the left outlet (heat exchanger) side. A rise in temperature at the thermostatic bulb results in a reversed effect.

### Two-way Temperature Regulating Valve

The two-way temperature regulating valve (fig. 6-16) is normally installed in the chilled water



55.331

Figure 6-16.—Two-way temperature regulating valve.

supply to the heat exchanger with the thermostatic sensing bulb installed in the distilled water outlet from the heat exchanger. It is shown on both figures 6-7 and 6-8. The basic operation of the two-way temperature regulating valve is the same as the three-way temperature regulating valve. If the temperature of the distilled water is above the desired temperature, the two-way valve gradually opens to increase the flow of chilled water through the heat exchanger, which keeps the distilled-water temperature at the desired point.

Both the three-way and two-way temperature regulating valves have a manual override feature to provide uninterrupted service, if and when the thermostatic assembly fails, due to damage to the capillary tubing or any other component of the thermostatic assembly. With the use of the manual override wheel, you can set the valve plunger/piston in the required position to operate the liquid cooling system by turning the manual override wheel down (from right to left) until it touches the spiral pin in the valve stem. Beyond this point, the valve plunger/piston is forced down, allowing the flow of cooling medium through the valve. With the use of the installed thermometers, you can decide if more or less cooling is needed by turning the manual override wheel up or down. The use of the manual override inhibits the thermostatic assembly and should only be used when the thermostatic assembly is inoperable.

Corrective maintenance of the regulating valve consists of inspecting the valve for leaks and for freedom of stem movement, adjusting the set point at which the valve regulates, renewing the thermostatic assembly, and cleaning and restoring valve parts. Any time that you remove a valve, you should center punch a dot code on each piece to ensure that the valve and piping are installed in the original configuration. The three-way valve can be turned around, and the problem could go unnoticed until you try to align the temperature regulation of the cooling system. There are individual manuals for the temperature-regulating valves and they should be closely followed. For example, if you remove the top of the thermostatic assembly without chilling the temperature probe, the bellows will expand and rupture, making the unit worthless. To verify that the thermostatic assembly has failed, close valves upstream and downstream of the thermostatic bulb, drain the unit below the location of the bulb, and remove the bulb from its well. Place the bulb in a suitable vessel and observe the valve stroke while the bulb is alternately heated with hot water and cooled with cold water. If the valve thermostatic assembly does not respond, it has lost its thermostatic charge, and a new unit must be installed.

## FLOW REGULATORS

You will encounter many different types and sizes of flow regulating devices used in both the primary and secondary cooling systems. They are used to reduce the pressure or the flow of coolant through a cooling system.

The orifice plate is found primarily in the seawater cooling system. It is the simplest design of a flow regulating device, consisting of a steel plate with a hole in it. With constant known seawater pressure and with a given hole size, the volume of water through the device can be determined. The use of an orifice plate is limited to where the input water pressure is essentially constant, such as the ship's firemain. The orifice plate is normally installed between two pieces of flanged pipes upstream from the heat exchanger as shown in figures 6-6 and 6-7. This will reduce the ship's firemain pressure below the pressure in the secondary cooling system. As we have indicated earlier, should one of the heat exchanger tubes fail, the seawater pressure is lower than the distilled water pressure; therefore, it would not contaminate the secondary cooling system. The secondary cooling system would force distilled water into the primary cooling system. A ruptured heat exchanger tube or a bad single tube sheet in a heat exchanger would give no visual indication of water loss except for the indication on the expansion tank sight glass.

To stabilize the flow of seawater and to prevent jet erosion of the heat exchanger and associated piping, the orifice plate should be installed with at least 15 pipe diameters of straight pipe upstream from the heat exchanger. When there is a drop in the heat exchanger primary input pressure and the seawater supply pressure has not changed, you should first check the duplex strainer differential pressure gage to ensure that the duplex strainer is clean. Then the orifice plate should be inspected for deposits or particles that could restrict the seawater flow. You should also

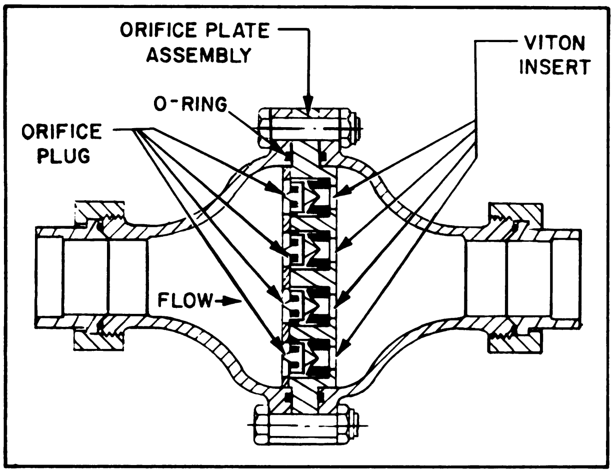


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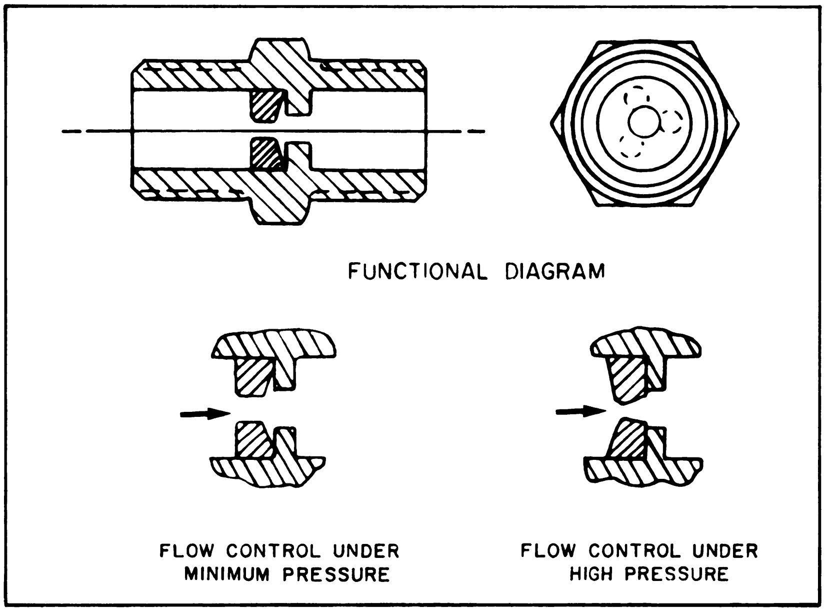
Figure 6-17.—Constant flow regulator.

inspect the orifice plate for erosion damage of the hole diameter. The orifice plate should be replaced when there is an increased flow of seawater to the point that it could damage the heat exchanger. Never use the seawater valves to throttle (partially close) the flow of seawater in the primary cooling system, because the seawater will erode the internal parts of the valve. The damage to the valve would require extensive repair or replacement, because the valve would no longer close properly.

When used with the chilled-water system, the constant flow regulator (variable orifice) (fig. 6-17) is installed downstream from the heat exchanger. This restricts the flow from the heat exchanger and keeps the heat exchanger fully submerged for greater efficiency (heat transfer). This type of flow regulator is not used in the seawater system because the internal parts would easily become fouled with marine growth and deposits. The operation is dependent on the movement of the orifice plugs (neoprene) to regulate the flow of water.

Another type of flow-regulator valve (equipment flow) used primarily with electronic equipment to regulate the flow of distilled water through the individual cabinets and components is shown in figure 6-18. It maintains a constant flow of distilled water with limited changes in the input pressure. At the minimum water flow, the total amount of water is passed through the


FUNCTIONAL DIAGRAM
FLOW CONTROL UNDER MINIMUM PRESSURE
FLOW CONTROL UNDER HIGH PRESSURE

55.333

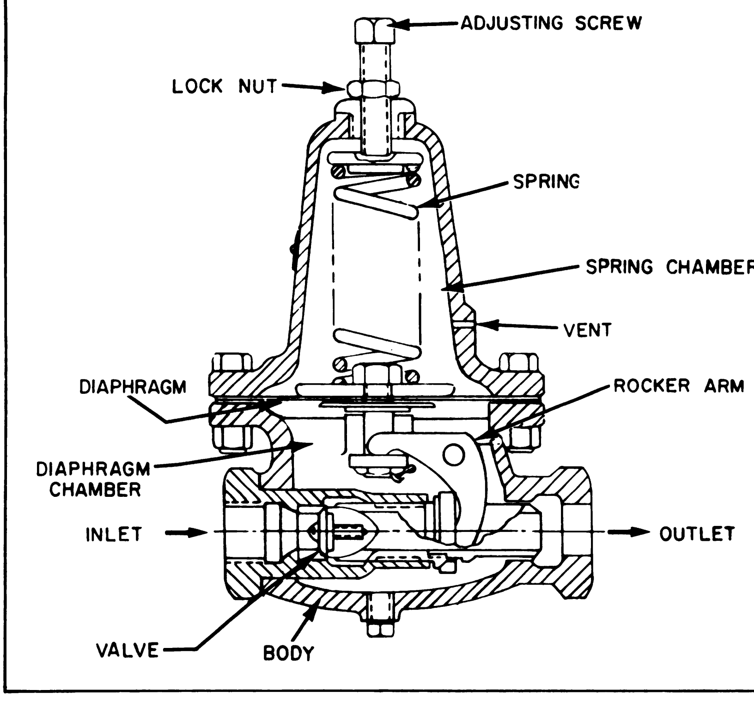
Figure 6-18.—Equipment flow regulator.

device. As the flow of water increases to the flow regulators maximum limit, the water flow is restricted by the inserts movement, which causes the hole size to decrease. In this way, the flow of water is regulated. The amount of water that the flow regulator will pass is usually stamped on the side of the regulator. This is because the external dimensions are usually the same for differently rated regulators.

The nominal flow rate of the equipment-flow regulator can be from one-half to more than 12 gallons per minute. It is normally used with a pressure-regulating valve. You should be aware that this type of regulator can deteriorate over time. The insert can become distorted and cause a reduction in the flow of water. With a drill index set, you can use the back of a drill bit to measure the hole size and compare it to a known good constant-flow regulator or the equipment manual. Do not drill out the insert to restore it to the proper size, because it will become distorted. Its distorted shape would prevent the insert from regulating the distilled water flow.

The pressure-regulating valve (fig. 6-19) is used to regulate a major section of the cooling system; whereas, the flow regulator is normally used to regulate an individual feeder line to an individual component or cabinet. The pressure-regulating valve usually has a pressure-relief valve downstream from it to protect the equipment from being over pressurized. Should a failure occur in the pressure regulating valve, the pressure-relief valve would keep the water pressure at a safe level to prevent equipment damage.

The operation of a typical pressure-regulating valve is as follows: When a drop in downstream (outlet) pressure occurs, the pressure in the diaphragm chamber is lowered concurrently. The downstream side of the valve is connected to the diaphragm chamber through a narrow opening



55.334

Figure 6-19.—Pressure regulator.

along the periphery of the piston. The spring is allowed to force the diaphragm downward releasing the tension on the rocker arm, and the inlet pressure opens the valve. The outlet pressure increases to the preset level, and the static control chamber pressure balances the valve spring to maintain a regulated downstream pressure to the served equipment.

You should take the following precautions with this type of valve. Ensure that the locknut is loose before you adjust the adjusting screw; otherwise, you could strip the threads of the brass spring chamber. If water should start leaking out of the vent, the valve should be serviced for a leaking diaphragm. This should be done before it ruptures. The vent should never be plugged or painted over to inhibit its operation.

If you should remove a flow regulator or a pressure regulator, make certain that you reinstall it correctly, because it can be installed backwards. Look for an arrow for direction of flow or the inlet and outlet stamped on the body of the device. Pipe-joint sealant should be used only on the male pipe threads and not closer than one thread to the open end to seal the device. Improper use of Teflon® tape can result in the tape being cut loose and circulated in the cooling system, which could plug up a small component.

## FLOW MONITORING DEVICES

Most systems incorporate one or more types of devices to monitor the flow of distilled water through the system to ensure that the electronic equipment is supplied with an adequate flow of distilled water. A low-flow switch is normally found in the secondary cooling system to monitor the overall coolant flow. It is electrically connected to a common alarm circuit to warn personnel when the system flow rate drops below a specified minimum value. A typical cooling system low-flow switch is shown in figure 6-20. The main operating parts consist of a hermetically-sealed reed switch and a permanent magnet attached to an internal shuttle. With the proper flow of coolant, the shuttle moves the magnet up and away from the reed switch. This keeps the reed switch contacts open. When the coolant flow drops below the minimum for a flow switch, the shuttle is forced down by the spring to a balanced condition against the flow of the distilled water. The magnetic field is now close enough to cause the reed switch to close and activate the low-flow alarm.

A much smaller flow switch is used in electronic equipment to monitor the flow to individual components. A typical equipment flow

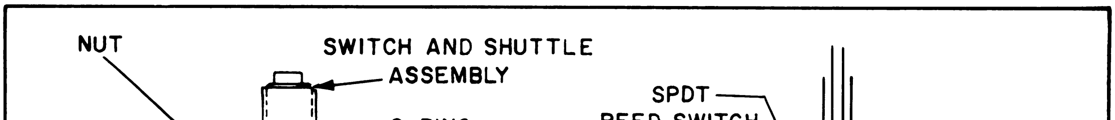


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Figure 6-20.—Cooling system flow switch.

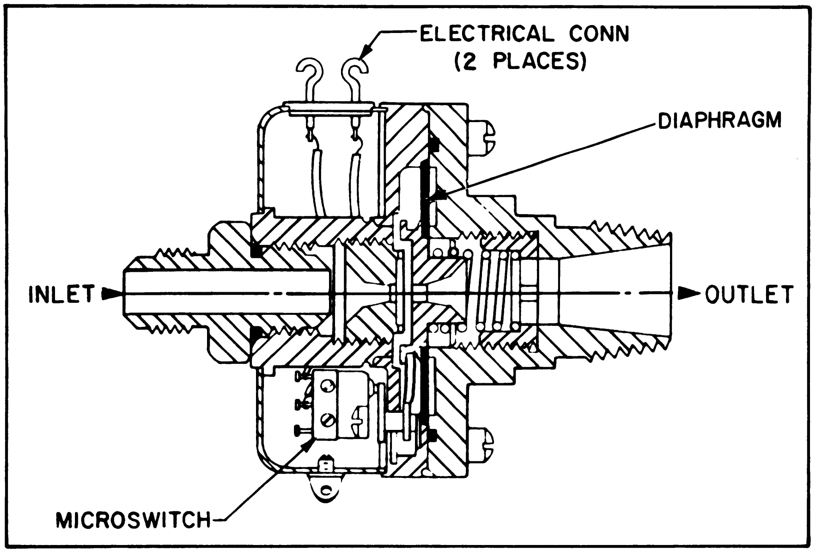

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**Figure 6-21.—Equipment flow switch.**

switch is shown in figure 6-21. The one depicted contains a fixed orifice.

The flow of water through the orifice causes a pressure drop across it. This pressure drop causes the diaphragm to move against the spring. When the differential pressure (pressure drop) is sufficient, the microswitch will activate to indicate that the switch has the proper flow through it. You should be sure that the flow switch is defective before overhauling or replacing it. The problem could be a partially closed supply/return valve, obstruction in the coolant line, insufficient coolant pressure, or many other things. By using the coolant system pressure gages and/or the installation of a permanent or a temporary in-line flowmeter, you should be able to correctly isolate the problem.

In the secondary cooling system, a full-flow system flowmeter (figs. 6-6, 6-7, and 6-8) is provided to enable you to monitor the total system flow rate for troubleshooting purposes. There are three types of system flowmeters installed aboard ship. All of them serve the same functional purpose of monitoring coolant flow rate. You will encounter the venturi-type flowmeter, orifice-type flowmeter, and the rotameter flowmeter. Most systems incorporate one secondary coolant flowmeter and one or more smaller flowmeters to ensure that the electronic equipment is being supplied with an adequate flow of coolant.

In the venturi-type flowmeter (fig. 6-22), as the coolant approaches the contracted portion (throat) of the meter, its velocity must increase as it flows through the contracted zone (throat). The angle of approach is such that no turbulence is introduced into the stream. A pressure tap is located at the side wall in the pipe ahead of the meter, and another one is located at the throat. The increase in velocity of the coolant water through the throat results in a lower pressure at the throat. The flow rate is proportional to the difference in pressure between the two taps. The gradual tapering of the meter walls back to pipe size downstream of the throat allows the coolant water to slow down with a minimum of lost energy. This allows a recovery of nearly 99 percent of the pressure on the approach side.

To monitor the amount of flow through the venturi-type flowmeter, a differential pressure gage is used to monitor the pressure difference between the two pressure taps. A calibration chart is usually supplied with the flowmeter to convert the different pressure to gallons per minute (gpm), or the face of the meter may indicate readings in gpm.

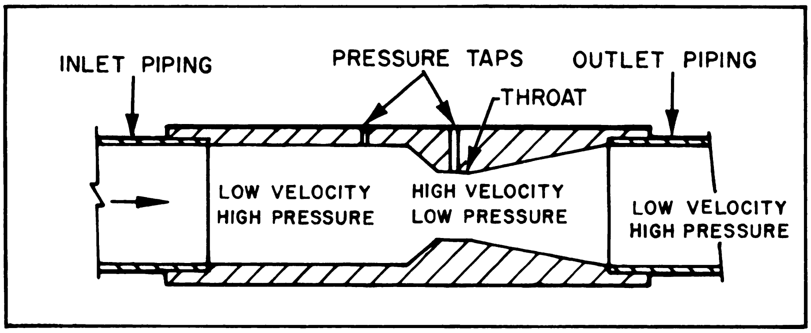

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Figure 6-22.—Venturi flowmeter.

The orifice flowmeter works in the same manner as the venturi flowmeter, but its construction is much simpler and less expensive to manufacture. In place of the tapered throat, the orifice flowmeter uses a flat plate with a hole in it, which causes a considerable loss of pressure downstream. The efficiency of this type of flowmeter can be as low as 65 percent.

The rotameter (fig. 6-23) is a variable area orifice meter that functions by maintaining a

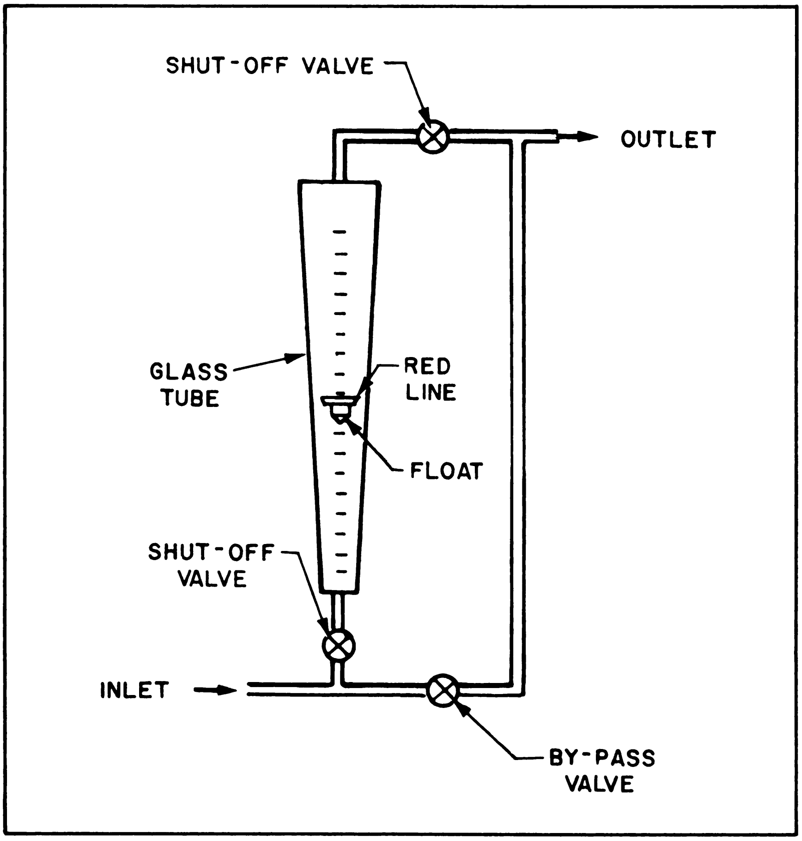

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Figure 6-23.—Rotameter.

constant differential pressure with varying flow. The rotameter consists of a float positioned inside a tapered, tempered glass tube by the action of the distilled water flowing up through the tube. The flow restriction is the space between the float and the tube wall. This area increases as the float rises. The differential pressure is fixed, depending upon the weight of the float and the buoyant forces resulting from the combination of float material and distilled water specific gravity. The tapered tube of the rotameter is usually glass with calibration marks reading directly in gpm. The major advantage of a rotameter over the venturi orifice meter is the visibility of the coolant. This allows quick determination of excessive entrained air in the coolant.

## CIRCULATING PUMP

Each cooling system has two secondary distilled water circulating pumps (fig. 6-24), which are identical in construction and capacity. One pump is designated for service, and the other is held in standby in case the designated pump fails. Should the pump designated for operation fail, then the standby pump would be used in its place. The pumps should be operated alternately (every other week) to prevent deterioration of their shaft seals, to equalize wear, and to permit PMS actions to be performed regularly.

The two circulating pumps used in the liquid cooling system are single-stage centrifugal pumps closely coupled (pump is built onto the motor) to a constant-speed electrical motor. You may run into an older system that uses a separate pump and motor joined by a flexible coupling. The centrifugal pump has two major elements—the impeller rotating on the extension of the electric motor shaft and a casing that is called the impeller chamber. The impeller imparts the initial velocity to the coolant. The impeller chamber collects the high-velocity coolant from the impeller and guides it to the pump outlet. A mechanical shaft seal is used to eliminate external leakage. This seal is lubricated and cooled by water ducted from a high-pressure zone of the pump. You will find a vent valve located on the top of the pump casing to remove air and ensure the pump is primed with coolant.

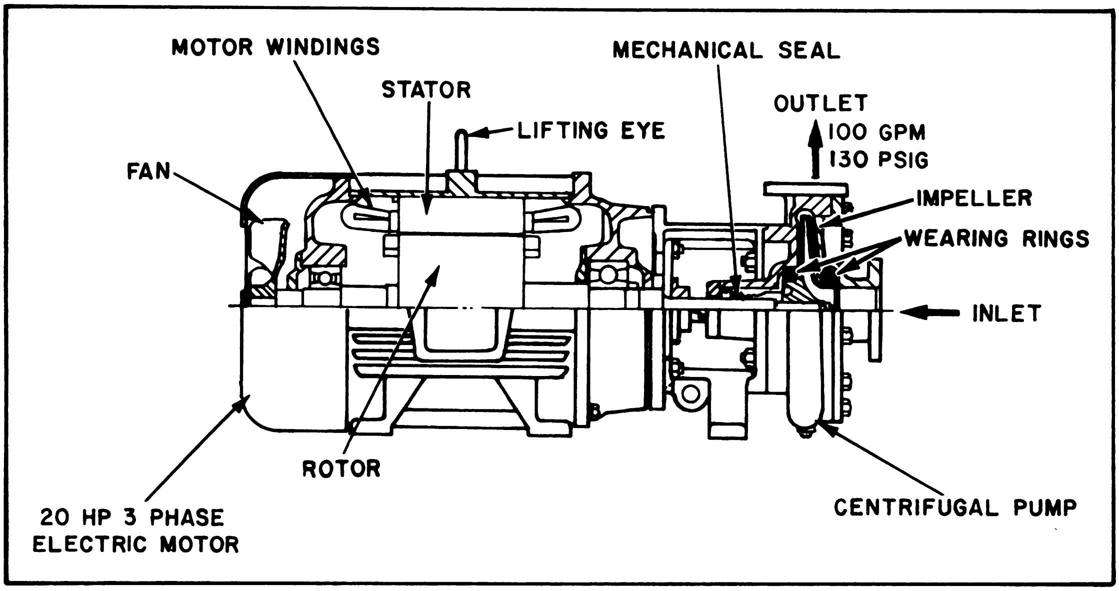

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Figure 6-24.—Distilled water circulating pump.

Located at the outlet of each pump is a check valve to prevent coolant from the outlet side of the operating pump from circulating to the return side of the coolant system through the standby pump. Hand-operated valves at the pumps are used to isolate the pumps so they can be removed for maintenance.

Each secondary circulating pump is rated in gallons per minute (gpm) output at a specified head pressure in pounds-force per square inch gage (psig) pressure, or in feet of water. The rating is usually at the pump's maximum efficiency point, and it will vary depending upon the pump design. On all pumps, as the output pressure increases, the output flow decreases, and vice versa. This relationship is almost linear but differs with different pump designs. However, this condition means that if a restriction is placed in the pump output lines, the pressure will increase and the flow will decrease. The restriction could be a partially closed hand valve, dirty filter, damaged or crimped piping or hose, and so forth.

In figures 6-6, 6-7, and 6-8, the pump performance indicators are the suction and discharge pressure gages and the system flowmeter. If you start a pump and pressure fails to build up, you should exhaust air through the vent cock on the top of the pump casing. You should ensure that the suction valve is fully opened and there is pressure on the pump suction pressure gage. If flow doesn't develop, check for clogging and wear.

You should not operate a pump without coolant flow. Some pumps have a small recirculating line that enables the pump to recirculate coolant from the discharge side of the pump to the suction side. This provides for a flow of coolant through the pump if an inlet/outlet valve to the pump is closed with the pump running. Whatever the case, you should keep in mind that the operation of a pump without the normal flow of coolant through it will result in overheating and seizure of the pump.

Corrective maintenance of the circulating pump consists of repairing leaks, replacement of the mechanical seal, and cleaning the internal parts. This type of maintenance is performed by personnel of the ship's engineering department. You should provide assistance if it is needed.

## DEMINERALIZER

The secondary cooling system water purity is maintained in an ultrapure state by a demineralizer. By maintaining the coolant at a high degree of purity, you minimize corrosion and the formation of scale on the radar unit. Corrosion or scale on a high-heat-density component such as waveguide dummy loads and klystrons results in the formation of a thermal barrier. The thermal barrier reduces the effectiveness of heat transfer at normal operating temperatures. This leads to premature failure of the components.

The demineralizer (figs. 6-6, 6-7, and 6-8) is connected between the secondary cooling system supply and return lines to circulate water through it. The demineralizer is sized so that 5% of the cooling system volume passes through the demineralizer every hour. The coolant is purified by organic compound adsorption (if required), oxygen removal, ion exchange processes, and submicron filtration. Shown in figure 6-25 is a typical three-cartridge demineralizer. Some demineralizers use only two cartridges; one of the cartridges is a combination cartridge that provides organic compound adsorption, if it is required.

The input supply valve to the demineralizer unit, depicted in figure 6-25, must be adjusted on system start-up, and periodically thereafter to maintain the correct flow rate through the flowmeter. Too high a flow rate can damage the cartridges. If the flow rate cannot be increased to the proper rate with the inlet supply valve fully open, you should check to ensure that the outlet valve is fully open.

The submicron filter is used to remove small particles from the coolant flow having a size

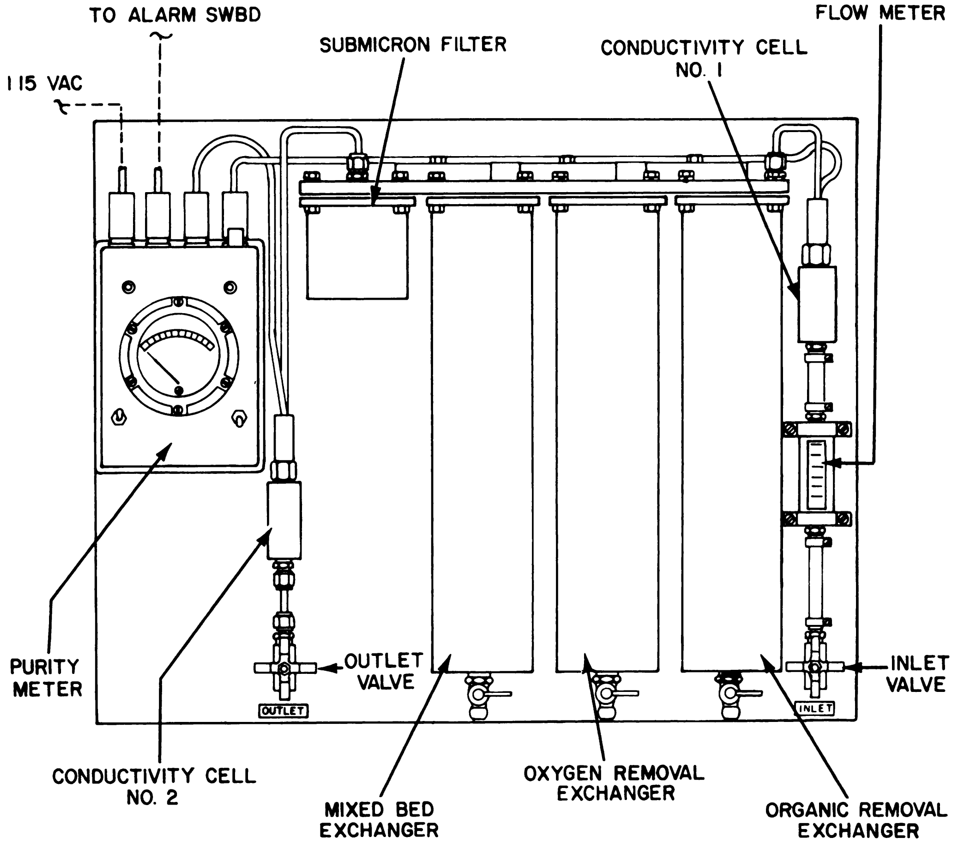

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Figure 6-25.—Demineralizer.

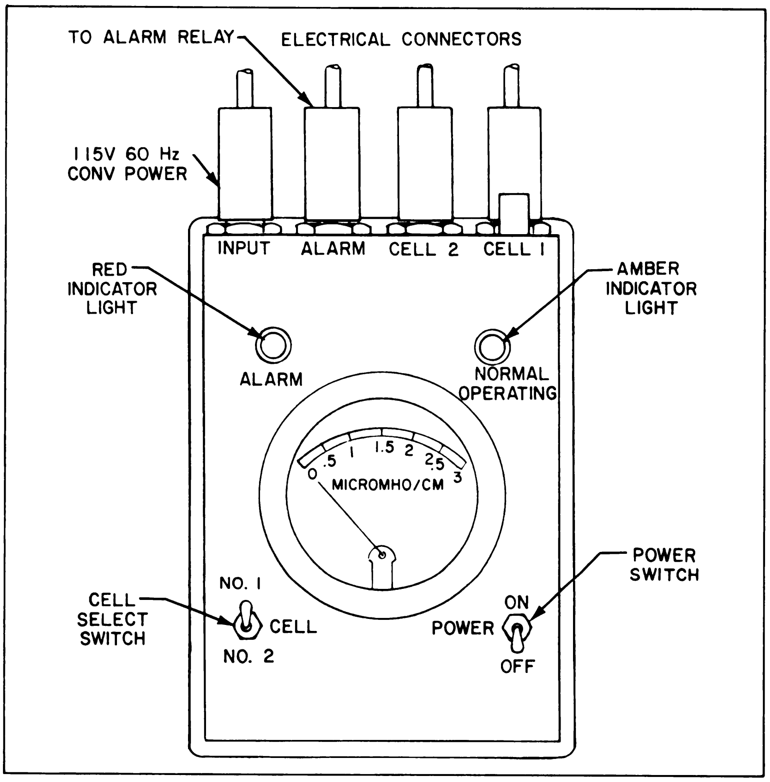
greater than 0.5 micron. If the filter becomes clogged, it also reduces the flow of coolant. This necessitates a change of the filter cartridge or filter sheet (membrane). To change the filter, the demineralizer valves must be properly positioned.

If the filter cartridge or membrane continually becomes clogged (about one-half hour or less after replacement), the usual cause in the distilled water system is the presence of bacteriological impurities. Bacteriological impurities introduced into the secondary liquid cooling system using distilled water may exist in the demineralizer cartridges and/or the whole secondary cooling system. If the bacteriological impurities are in the whole secondary cooling system, the growth rate in a warm water environment could be of a magnitude that exceeds the capability of the demineralizer. You will have to determine the source and magnitude of contamination. However, it should be noted that bacteriological contamination in a secondary cooling system that uses distilled water and ethylene glycol is highly improbable.

Improper handling or storage of the cartridges could cause the cartridge to be a source of contamination. You should always store the cartridges in a cool dry area. Exposure to heat hastens the growth of any biological contaminates that may have entered the cartridges. You will encounter three different types of cartridges. The first cartridge is the organic removal cartridge. It contains granulated activated charcoal (carbon) that removes large organic molecules and chlorine by adsorption. It is always installed in the first exchanger (if required) to prevent organic molecules from fouling the remaining cartridges. The second cartridge is the oxygen removal cartridge. It is composed of anion resins that remove oxygen from the water by ion exchange of sulfite ions to sulfate ions. By conducting a standard oxygen test (or if the cooling system has an oxygen analyzer installed), the quality of the outlet water from the demineralizer can be tested for oxygen content so that you will know when to replace an oxygen cartridge. When the oxygen cartridge is near exhaustion, it will have a urine odor, which is given off by the sulfate. The third cartridge is the mixed-bed cartridge. It is filled with cation (positive charge) and anion (negative charge) resins, which remove solids, dissolved metals, and carbon dioxide. The charged resins exchange ions with the contaminates, thereby removing them and leaving pure deionized coolant. You should replace the mixed-bed cartridge when the purity meter indicates a low outlet purity.

As indicated in figures 6-25 and 6-26, two conductivity cells monitor the coolant through the demineralizer. The first cell measures the purity of the coolant as it enters the demineralizer. The second purity cell is used to measure the purity of the coolant as it leaves the demineralizer. The conductivity cell consists of two electrodes immersed in the coolant flow path. The electrodes measure the conductivity of the coolant, which varies with the amount of ionized salts dissolved in it. If the impurity content increases in the coolant, the purity meter indicates higher conductance.

On some purity meters, the purity of the coolant is displayed as resistivity. In this type of meter, an increase in the impurity of the coolant



55.341

Figure 6-26.—Purity meter.

causes the meter to indicate a low resistivity. Conductance is the reciprocal of resistance, and is measured in micromhos/cm. Resistivity is measured in megohms/cm. You can convert from conductivity to resistivity by taking the reciprocal of conductivity. Similarly, the reciprocal of resistivity is equal to the conductivity. A comparison of both ways of measuring the purity of the coolant is shown in table 6-1. The purity meter indications will vary with ionized salt concentration and the temperature of the coolant flowing through the cell. The temperature effect is canceled by a built-in temperature compensation circuit.

The inlet conductivity is compared to a preset value of cell conductance to actuate an alarm circuit when the purity of the water drops below the preset level. In addition, the purity meter provides direct readings of the water purity at the inlet and outlet of the demineralizer. Typical operating requirements for the demineralizer are conductivity 1 micromho/cm at 77 °F (resistivity 1 megohm/cm at 77 °F), oxygen content 0.1 ppm by weight, and mechanical filtration 0.5 microns absolute.

When water has been circulated through the system for extended periods of time, a high resistivity or low conductivity reading may be indicated on both input and output samples. This condition is highly desirable and indicates that all ionizable material has been properly treated, and that the demineralizer is maintaining a high degree of purity. When a system is filled with a fresh charge of water, it should be allowed to circulate for approximately 2 hours before comparing the input and output readings. During the initial circulation period, the resistivity readings vary because of the mixing action of water that has been treated by the demineralizer with the fresh charge of water. A properly operating system can supply water of acceptable purity in 4 to 8 hours. Water in a system that has been secured for any length of time should be of acceptable purity within 2 hours. The resistivity/conductivity reading required for a specific installation must be maintained for optimum operation of the cooling water system.

Your first indication of a problem in the demineralizer is usually indicated by abnormal purity meter readings (too low/high), an abnormal flowmeter reading, and/or a light and audible warning from the purity monitor. Some purity monitors can be tested for accuracy by a built-in test function on the meter to establish if the problem is in the purity monitor. If the purity monitor does not have a test feature, then use the calibration plug in place of one of the conductivity cells to test the operation of the purity meter. Most of the time, only routine maintenance is required to return the demineralizer to its normal operating condition.

**Table 6-1.—Distilled Water Resistivity Versus Conductivity Data**

| Resistivity (megohms-centimeters) | Purity | Conductivity (micromhos per centimeter) |
|---|---|---|
| 10.0 | ▲ | 0.1 |
| 2.0 | Increasingly better | 0.5 |
| 1.0 | water purity. | 1.0 |
| 0.5 | \| | 2.0 |
| 0.1 | | 10.0 |

Maintenance of the demineralizer consists primarily of the scheduled replacement of cartridges (before they are exhausted) and clogged filters. Obtaining satisfactory service life from the cartridges and filters is largely dependent on minimizing external contamination. Replacement cartridges must be kept sealed and stored in a cool dry place until used. The circulating system must be kept tight to reduce the need for makeup water. Makeup water, in any case, should be as particle-free as possible and should not exceed 0.065 ppm chloride.

## OXYGEN ANALYZER

In some secondary cooling systems, an oxygen analyzer is installed to measure the amount of dissolved oxygen in the liquid coolant. The presence of oxygen causes oxidation that leads to the formation of scale in the cooling system. An oxygen analyzer has a oxygen sensor installed in the supply side of the secondary cooling system. The sensor is an electrolytic cell in an electrolyte solution or gel. A thin Teflon® membrane covers the end of the sensor, which is inserted in the coolant. The Teflon® membrane is gas permeable to the dissolved oxygen in the secondary coolant. This allows the oxygen to pass through the membrane. The oxygen reacts with the electrolyte, which causes a proportional change in the amount of current flow in the sensor. The sensor's electrical output is measured and displayed on the oxygen analyzer's meter. The meter is calibrated to read the oxygen content in parts per million or billion.

Because of solid state electronics and the few components used, the oxygen analyzer requires very little maintenance other than the cleaning and changing of the electrolyte in the sensor. When the meter on the analyzer requires frequent calibration because the meter readings are drifting or changing sharply, you should recognize that the analyzer has a bad sensor. When you clean and recharge the sensor, use caution to prevent contamination of the Teflon® membrane from the oil on your fingers.

## COOLANT ALARM SWITCHBOARD

The cooling system alarm switchboard (SWBD) monitors various conditions to alert you to a problem that may develop in the cooling system. When an abnormal condition occurs, the alarm SWBD indicates the fault condition with both a visual and an audible alarm. The alarm SWBD usually has several remote bells and lights in CIC and other electronic spaces aboard ship to indicate a fault condition that has occurred. The alarm SWBD is located in CIC or the coolant pump room. There are several standard types of alarm switchboards used throughout the Navy. A common type of alarm SWBD is shown in figure 6-27.

On the main alarm panel, there are two GROUND INDICATOR LAMPS (fig. 6-27) to indicate the presence of a ground in the alarm system. All shipboard alarm panels and remote sensors are electrically isolated from the ship's ground. The only exception is the ground fault detector, which is connected to ground for ground monitoring. If one or both lamps light, you should have the alarm SWBD and its remote sensors serviced by an IC Electrician (who has maintenance responsibility) to remove a very dangerous shock hazard. The AUDIBLE SILENCE CONTROL is a two-position switch that permits silencing (VISUAL POSITION) the audible alarm on the main panel. The ALARM lamp on the main panel is lighted when the AUDIBLE SILENCE CONTROL is placed in the VISUAL position, and the system is in an alarm condition.

The lower half of the alarm panel (fig. 6-27) holds the alarm modules that are connected through the alarm panel to the remote sensors. On the panel depicted, there are only five alarm modules used, while the rest is blanked off with covers. Should additional remote sensors be installed at a later date, a new alarm module is plugged into the lower panel for each sensor installed. Each alarm module includes a center-divided lighted display. Either half can independently display a steady red light, a flashing red light, or no light, depending upon the circuit logic. The six possible combinations of alarm module lights and the appropriate audible

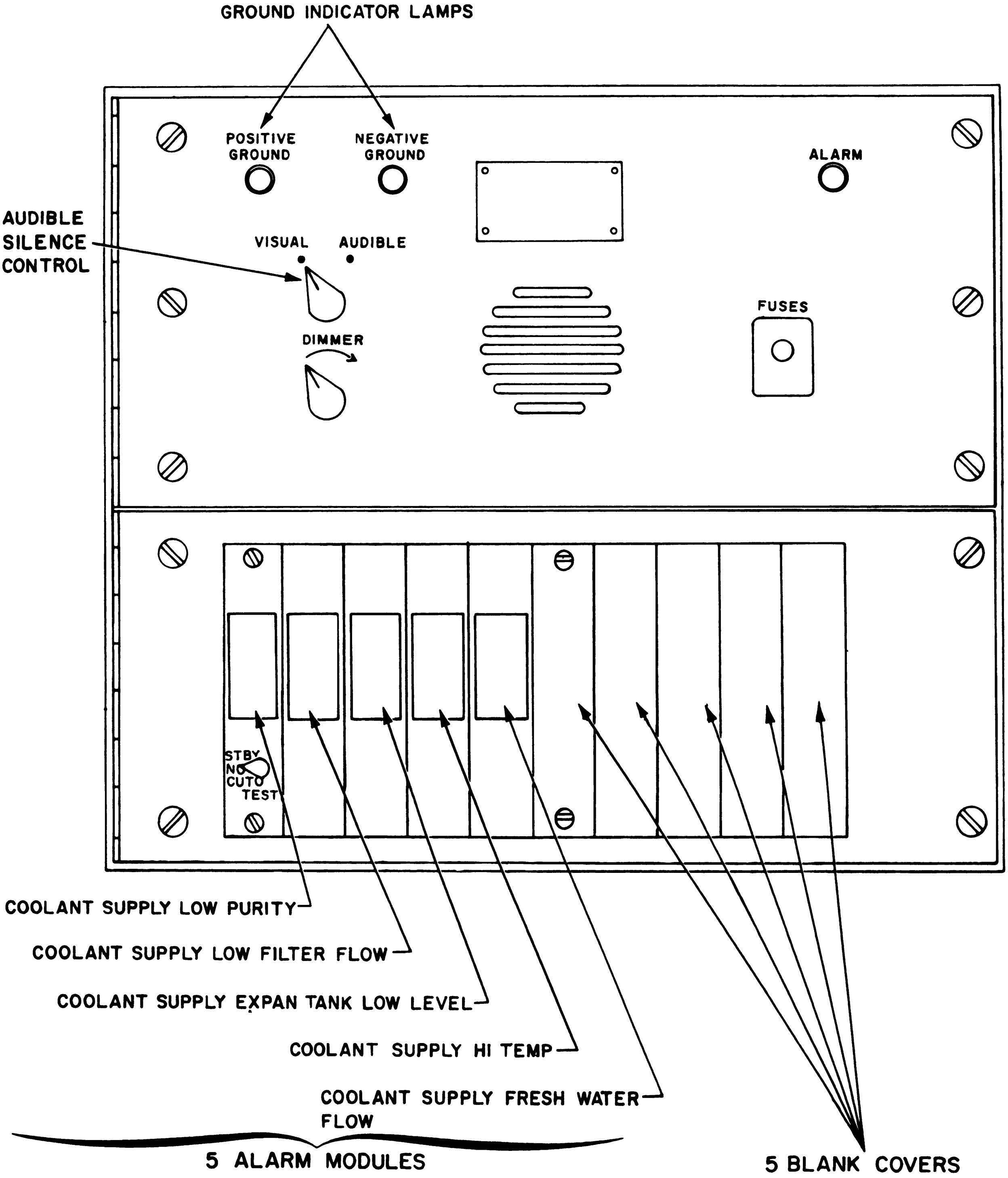


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Figure 6-27.—Cooling system alarm switchboard.

alarm are shown in figure 6-28. Located on the lower half of each alarm module is a four-way position switch that allows you to place the individual alarm module in the following modes:

- NORMAL. This is the normal operation mode. With the sensor contacts open, the upper indicator lamp in the module will be on steady while the lower lamp is off. If an alarm condition occurs, the sensor contacts will close; the upper lamp will then flash while the lower lamp remains off and an alarm command from the module actuates a tone generator, producing a wailing alarm. If the sensor loop is open-circuited, with the selector switch in the normal position, the alarm module signals a supervisory failure; in this case, the upper lamp will be off while the lower lamp will be steadily on, and the tone generator will come on, producing a pulsating alarm.

- STANDBY. This is the position for acknowledging an alarm. If the selector switch is

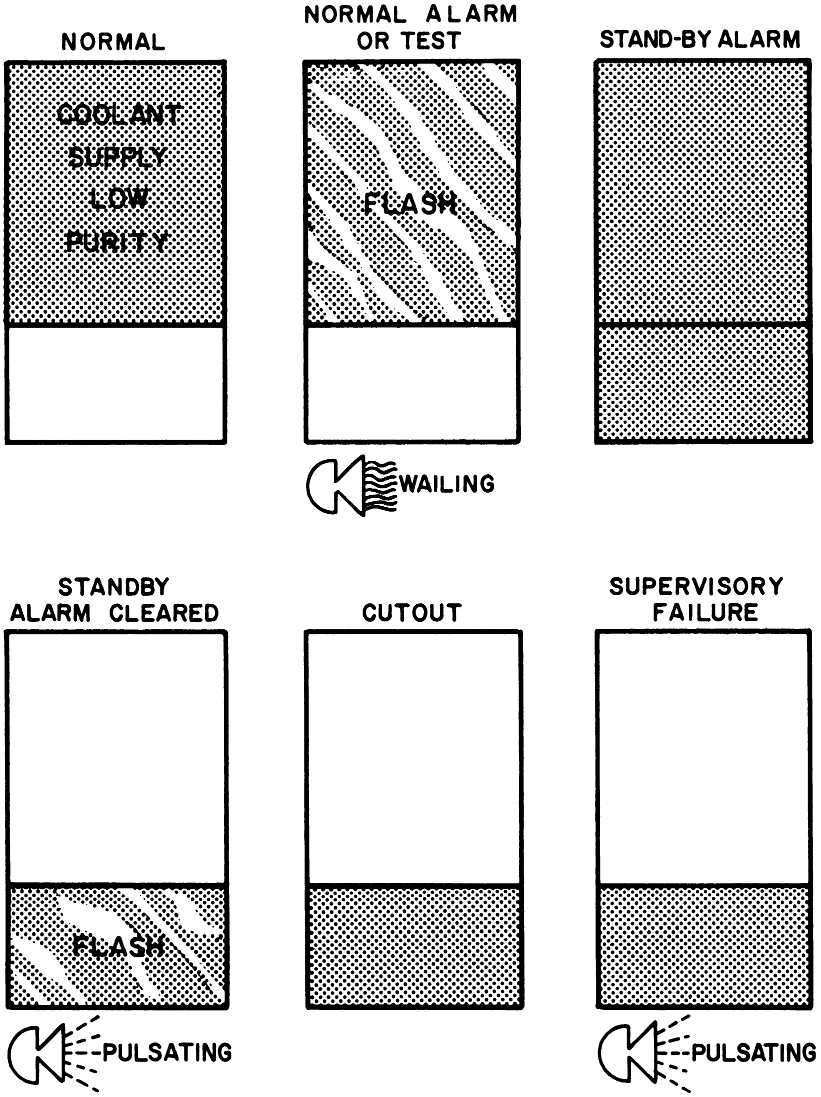

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Figure 6-28.—Alarm switchboard visual displays and audible outputs.

moved from the normal to the standby position during an alarm condition, both the upper and lower indicator lamps will be steadily on and the audible alarm will be silenced. When the alarm condition is cleared with the selector switch in the standby position, the lower lamp changes to a flashing mode and the upper lamp goes out. Also, a command is fed to the tone generator, producing a pulsating alarm. This pulsating alarm signal informs the operator that the selector switch should be returned to the normal position.

- CUTOUT. With the selector switch in the CUTOUT position, the upper lamp is out while the lower lamp is steadily on. In this position, power is removed from the sensor loop to facilitate maintenance.

- TEST. This selector switch position simulates an alarm condition. The upper indicator lamp will be flashing while the lower lamp is off. A wailing alarm is produced.

Your proper response to the coolant alarm SWBD could mean the difference between a small service problem or the makings of a much larger disaster. For example, if the COOLANT SUPPLY EXPANSION TANK LOW-LEVEL alarm module senses a low coolant level in the expansion tank, immediate action must be taken. If the tank should empty, the pump will draw air into the lines and force it throughout the secondary cooling system. This would require an increase in the amount of maintenance required to correct the problem, because you would have to add coolant and then bleed the air out of the cooling system. It is better to add coolant before the tank becomes empty.

### COOLING SYSTEM MAINTENANCE RESPONSIBILITY

The most important responsibility that you have that will extend the life of the cooling system components and increase the reliability of the cooling system is how you schedule and perform preventive and corrective maintenance according to the Planned Maintenance System (PMS). Properly performed preventive maintenance drastically reduces the amount of corrective maintenance necessary. When cooling systems are neglected, they deteriorate very quickly. To restore the cooling system back to its proper performance, you may have to undertake extreme and costly repairs.

The PMS responsibility of the cooling system varies from one system to another. On some systems, you will find that the engineering department has the total responsibility of preventive and corrective maintenance. On other systems, you'll find that you share the maintenance responsibility jointly with the engineering department. In these situations, the FCs would probably perform the preventive maintenance and the engineers would perform the corrective maintenance on major components. When you are assigned the responsibility of maintaining the cooling system, you should perform the preventive maintenance in accordance with the Maintenance Requirement Cards (MRCs) to maximize the operation of the cooling system.

## RADAR DRY-AIR SYSTEM

For the optimum operation of todays modern high-powered search or fire control radar sets, waveguide systems used in both the low- and high-power areas of the radars are required to be pressurized with dry air. In some waveguide systems, dry air is used primarily to increase the dielectric constant inside the waveguide to prevent rf energy from arcing inside the waveguide. Arcing causes damage to the inside of the waveguide, and it also reflects a short circuit back to the power amplifier tube. The power amplifier could sustain major damage. Also, with the use of pressurized dry air, the problems of corrosion, contamination, collection of moisture and oil droplets (which affect preservation) are decreased. At the same time, the overall reliability of the waveguide system is increased.

In high-power waveguide runs, the dry air pressure is around 20 to 35 psig, which reduces the tendency for waveguide arcing to occur. The increased air pressure increases the dielectric (resistance) strength of the air. Arcs are less able to form.

In low-power waveguide runs, the dry air is on the order of 1 to 8 psig. The dry air is used primarily to prevent corrosion and contamination of the inside of the waveguide.

These effects are caused primarily by moisture in the waveguide.

The number of electronic equipment requiring dry air for operation has increased drastically in recent years. Central dry-air systems have been installed in many ships to overcome the problems of individual maintenance, repair, and supply support required by individual air dehydrators. There are, however, a large number of individual equipment dehydrators still in use. They are now being used as back-up systems should there be a failure in the ship's central dry-air system.

There are several methods that can be used to remove excess moisture from the air. One method is by freezing the air by means of a refrigerant to remove the moisture. The second method is to pass the air through a desiccant which adsorbs the moisture. Some dehydrators use a combination of the two methods to remove the moisture.

## CENTRAL DRY-AIR SYSTEM

The ship's central dry-air system is usually located in one of the ship's main engineering spaces and can be composed of a low-pressure (100 psig) air compressor, a Type I dehydrator, and either a Type II or III dehydrator. The air compressor compresses the air and then sends it to the Type I dehydrator (refrigerant). The Type I dehydrator is used to remove the majority of the water and oil in both liquid and gaseous vapor forms from the air. Next, the air is processed by a Type II (desiccant) or a Type III (combination of refrigeration and desiccant) dehydrator to remove the last traces of moisture. This last bit of processing causes the air to become electronic dry.

## DRY-AIR SYSTEMS

If you are involved with an equipment dry-air system, it is essential that you understand how to check the air for sufficient dryness. A high-power waveguide system requires dry air at a pressure of 25 to 35 psig with a dew point of −40 °F at atmospheric pressure.

Dew point is the temperature at which water vapor begins to deposit as a liquid (at atmospheric pressure unless otherwise stated). For example, when the dew point is given as −40 °F, this means that the excess moisture in the air will begin to condense at this temperature. Condensation appears as a fog or, if enough moisture is condensed, as ice crystals. The dew point is affected by the pressure of the air being measured. Air at −40 °F dew point (atmospheric pressure) contains approximately 120 parts of water per million parts of air (ppm). However, this same air at 30 psig has a dew point of about −21 °F. As you can see, you have to take into account the effects of pressure when you measure the dew point. The lower the dew-point reading (more negative/colder), the better the air quality.

The equipment air dryers installed in electronic equipment are desiccant dryers. The air is passed through a desiccant, which adsorbs the moisture. The more moisture the desiccant adsorbs, the dryer (lower dew point) the air becomes. You should know the basic operation of a desiccant air dryer so that you can perform PMS and trouble isolation.

## SHIPS AIR SUPPLY

Air from the ship's compressor is often contaminated with water and oil in the form of vapor and liquid. The compressor compresses the air into a smaller volume causing the relative humidity of the air to increase. When the compressed air is saturated (100 percent humidity), it no longer holds any more vapor. Further compression causes the formation of liquid to begin. Also, since most compressors use some form of lubricant, it too can get into the compressed air as a vapor or liquid. The ship's dehydrators can remove all contamination, both liquid and gaseous vapor. In the event of a failure in the central dry air system, the small air dryer (if installed with electronic equipment) can be placed into operation.

## EQUIPMENT DRY AIR

The purpose of the desiccant air dryer (fig. 6-29) is to remove oil and water in both forms, automatically and continuously, and to deliver clean, very dry air for pressurization of equipment waveguide. The air dryer is normally in the bypass mode. In this mode, input air is routed down through the selection valve and out of the dryer by way of the flow limiter. When placing the selection valve so that the dryer will process the air, you must first follow the dryer's start-up procedure.

This procedure ensures that wet air doesn't get into the waveguide systems when the dryer has been shutdown for an extended period. Basically, the procedure involves turning the electrical power on for the dryer and opening/closing of various

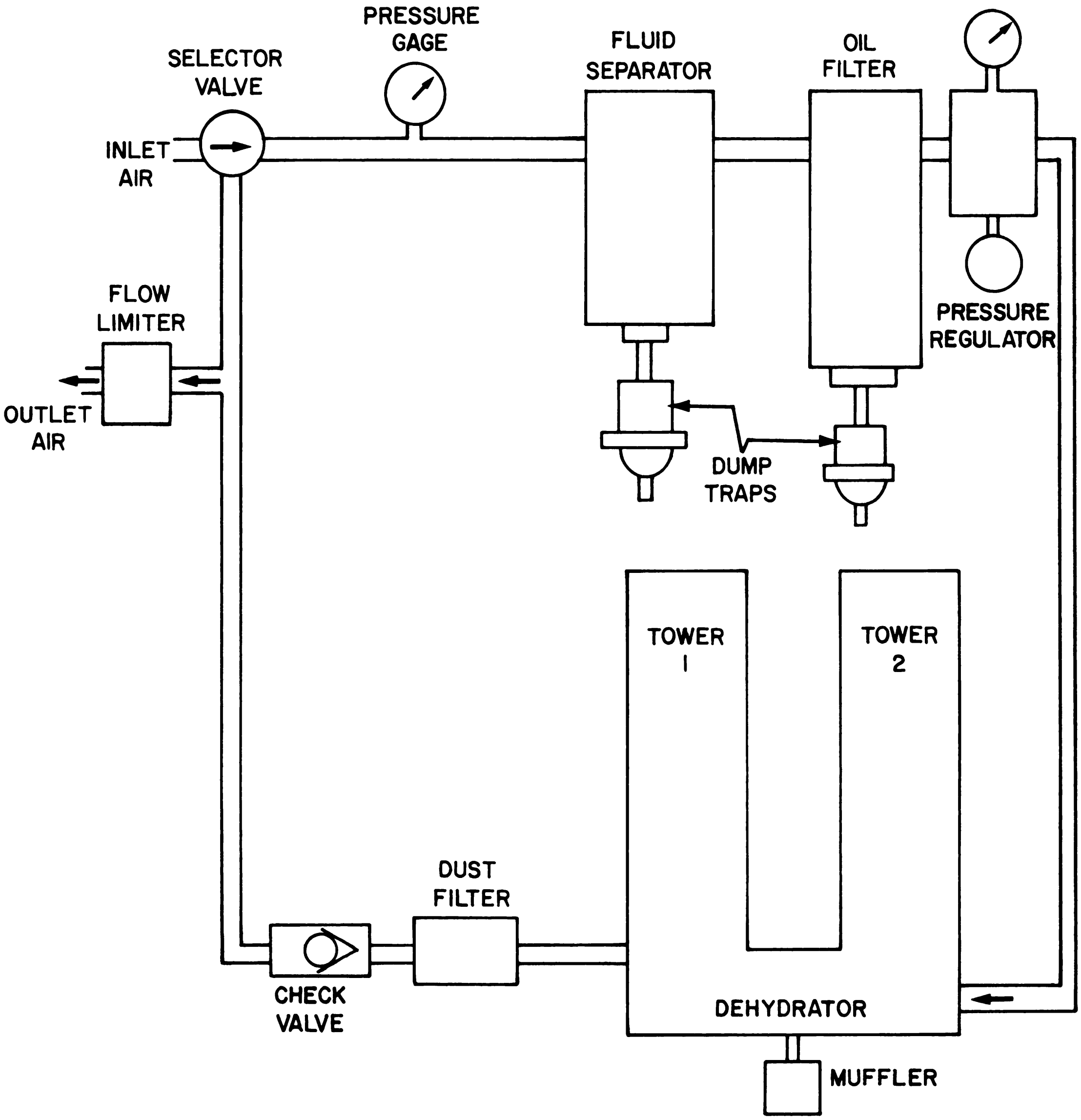

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Figure 6-29.—Desiccant air dryer.

valves to dump the air to the atmosphere. This is done until the dryer's air monitor indicates that the dew point is below −40°F at atmospheric pressure.

The operation of the air dryer is as follows: The input air (fig. 6-29) (selection valve is indicated) is first checked on the pressure gage for minimum air pressure (typically 80 psig). Input pressure that is too low inhibits the operation of the fluid separator.

The fluid separator extracts most of the free liquids from the airstream. Some oil and water mist, however, (extremely fine droplets) remain in the stream.

The liquid, thus collected, drains into the dump trap below the separator. When a sufficient amount has collected, the trap automatically opens to discharge the collected liquids under pressure into a waste line for disposal.

After the fluid separator, the air is passed through a telltale oil filter, which removes oil through a combination of mechanical means and absorption. The oil that is removed mechanically drains into a dump trap and is discharged into a waste line as in the fluid separator.

The oil that is absorbed causes the absorbing material to change color from pink to deep red, starting at the bottom, as it becomes saturated. Since the absorbing column is in a transparent plastic tube, the color change is visible. Before the color change reaches the red line on the column, the absorbing material is discarded and new material is installed.

At this point, liquid oil, liquid water, and some oil vapor have been removed from the air. The air is, in most cases, still saturated with water vapor and still contaminated with oil vapor.

After passing through a pressure regulator, which reduces the air presure and holds it constant, the wet air passes through the most important unit of the system—the purifier-dehydrator. The purifier-dehydrator performs a cleaning step by a process known as adsorption.

There is a difference between absorption and adsorption.

Absorption takes place in the telltale oil filter when it removes oil by soaking it up as a liquid (the same way that a sponge absorbs liquid water into its interior pores).

Adsorption is a surface and a molecular phenomenon. Mobile gaseous and liquid atoms or molecules are attracted to the surface of any solid because of unbalanced forces existing at the surface. Good adsorbents are those that present large surfaces per unit and have high attractive forces. One cubic inch of the adsorbent material used in this dryer has an adsorbent area greater than the area of two football fields.

The wet air passes through chambers filled with a molecular sieve type of desiccant, or adsorbing material. Vapor molecules are left behind on the desiccant and the air emerges clean and dry.

The dehydrator has two such chambers through which the air passes alternately. While one chamber is removing vapor from the air, a small portion of the dried air is routed through the second chamber to purge it of all collected vapors and to prepare it to do the drying during the next half cycle.

The reactivation of the desiccant is completely automatic, and unless slugs of entrained water or oil are permitted to enter the desiccant chambers, the material should not be replaced except at major overhaul. The fluid separator and the telltale oil filter, located upstream, prevent slugs of liquid from reaching the desiccant if they are kept in good operating condition.

The dust filter, located downstream from the dehydrator, removes any desiccant or other dust particles that might otherwise be carried along in the dry airstream. At the outlet of the drier unit, a flow limiter is used to prevent the electronic equipment from exceeding the capacity of the dryer. In normal operation, the flowmeter has no effect. However, should an air line or waveguide downstream from the dryer be opened, the flow limiter would prevent an exessive airflow beyond the capability of the dryer.

## DRYER COMPONENTS

In figure 6-29, the placement of the individual components is shown for a typical dryer. This is the order that you should expect to see them. The air dryer is a very reliable piece of equipment and with proper PMS can give you years of service between failures.

The operation of the dryer can be bypassed by changing the selector valve. With the selector valve in the position as shown, all air is routed through the dryer. Starting at the inlet, the individual operation of each major component will be discussed in depth. Let's begin with the fluid separator and its dump trap.

### Fluid Separator and Dump Trap

The fluid separator and dump trap consists of two interconnected assemblies, the separator and the automatic trap, connected together as shown in figure 6-30. The separator itself is a welded metal tank with in and out ports, an inlet pressure gage, a dump trap, and a sump drain port. There is also a pipe plug located in the top for testing the dump trap.

Air flows through the in port and a downcoming tube, and is exhausted into the tank. It then reverses its direction, flows upward to the top of the out-port tube, and reverses direction again to reach the out port.

Centrifugal forces at the two points of reversal and the slowing of the flow within the tank extract the entrained droplets of liquid. These collect at the bottom of the tank and drain into the dump trap. When the liquid level in the trap rises sufficiently, a float (through a connecting linkage) opens a valve to a waste line, and the collected liquid is blown out. When the float drops, the valve closes and liquid collects until the float automatically initiates another disposal sequence.

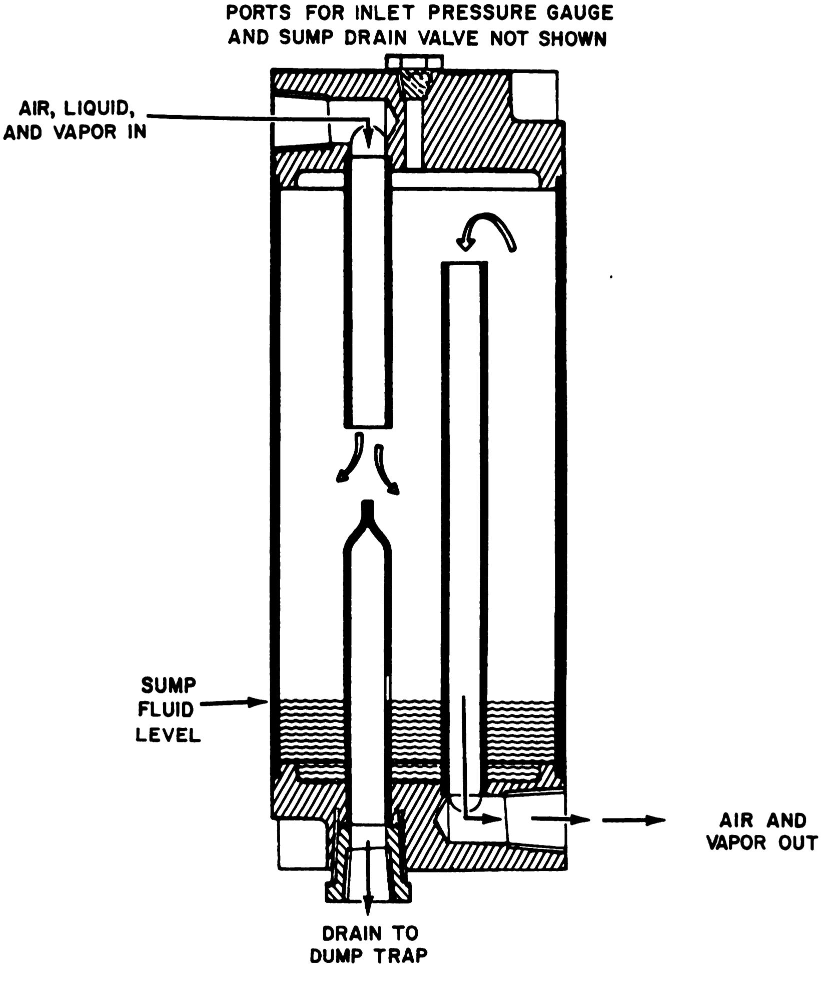

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Figure 6-30.—Fluid separator.

Operation of the float may be observed through a transparent trap bowl. The trap is also equipped with a manual drain, which is operated by pulling a button on the bottom of the trap.

### Telltale Oil Filter and Dump Trap

The telltale oil filter and dump trap are located downstream from the fluid separator and dump trap. It is designed specifically to remove oil from compressed air and to indicate by color the state of the oil removing material. This unit further purifies the air by removing small oil droplets that escape the fluid separator.

As shown in figure 6-31, the filter employs two direction changes of airflow and impingement surfaces to mechanically remove droplets; a mist separator to help small drops become larger and drop out; and an absorbing material to remove the remainder. The absorbing column, which is visible in a transparent tube, changes color from pink to dark red as it absorbs oil. Before the color change reaches a red line indicator, the filter element should be replaced.

Liquid oil drains, as collected, into an automatic dump trap for discharge into a waste line. This trap is identical to that used on the fluid separator; therefore, the same explanation and comments apply.

The combination of the fluid separator and the telltale oil filter removes entrained water and oil and some of the oil vapor from the supply air, provided that these units are properly maintained.

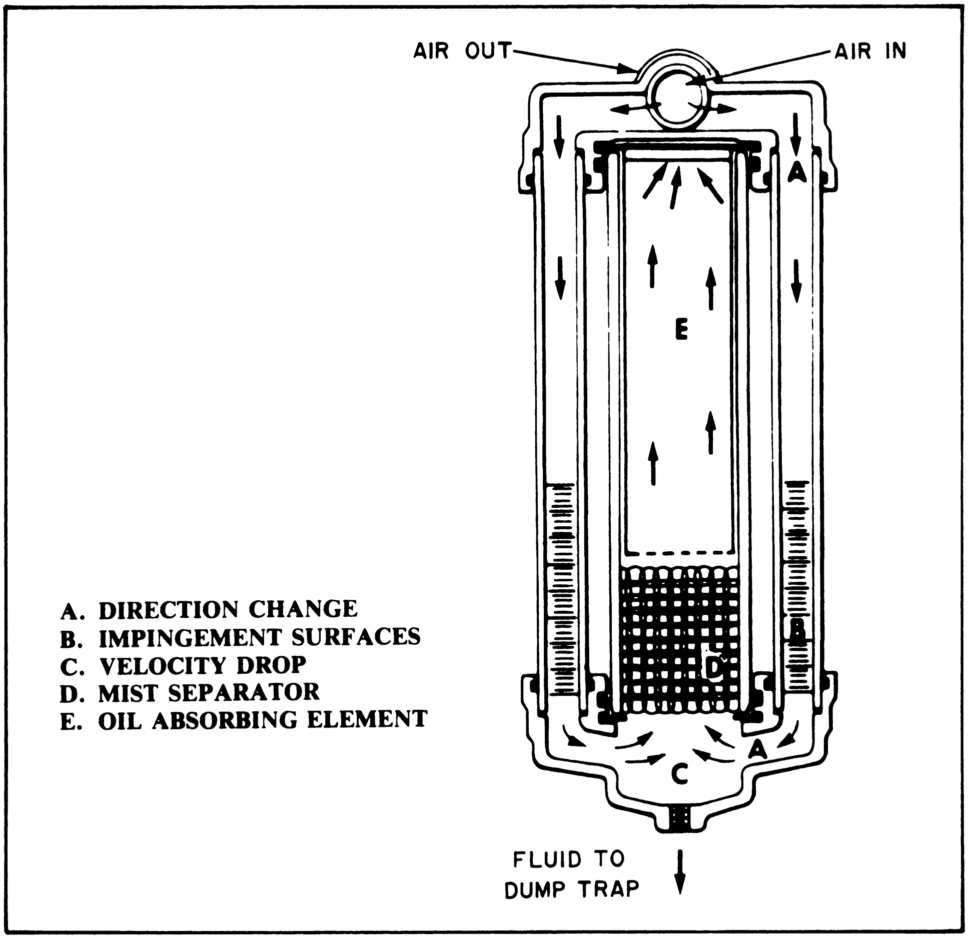

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Figure 6-31.—Telltale oil filter.

Water vapor and any remaining oil are removed in the dehydrator (fig. 6-29), which follows further downstream.

### Pressure Regulator

The pressure regulator (fig. 6-32) is a diaphragm-operated, pressure-reducing valve located downstream from the fluid separator and telltale oil filter. The diaphragm position governs the valve opening, maintaining a constant reduced output pressure. Compressed air is used to load the diaphragm. This is accomplished by bleeding air from the line through two needle valves, the body needle valve and the dome needle valve, into

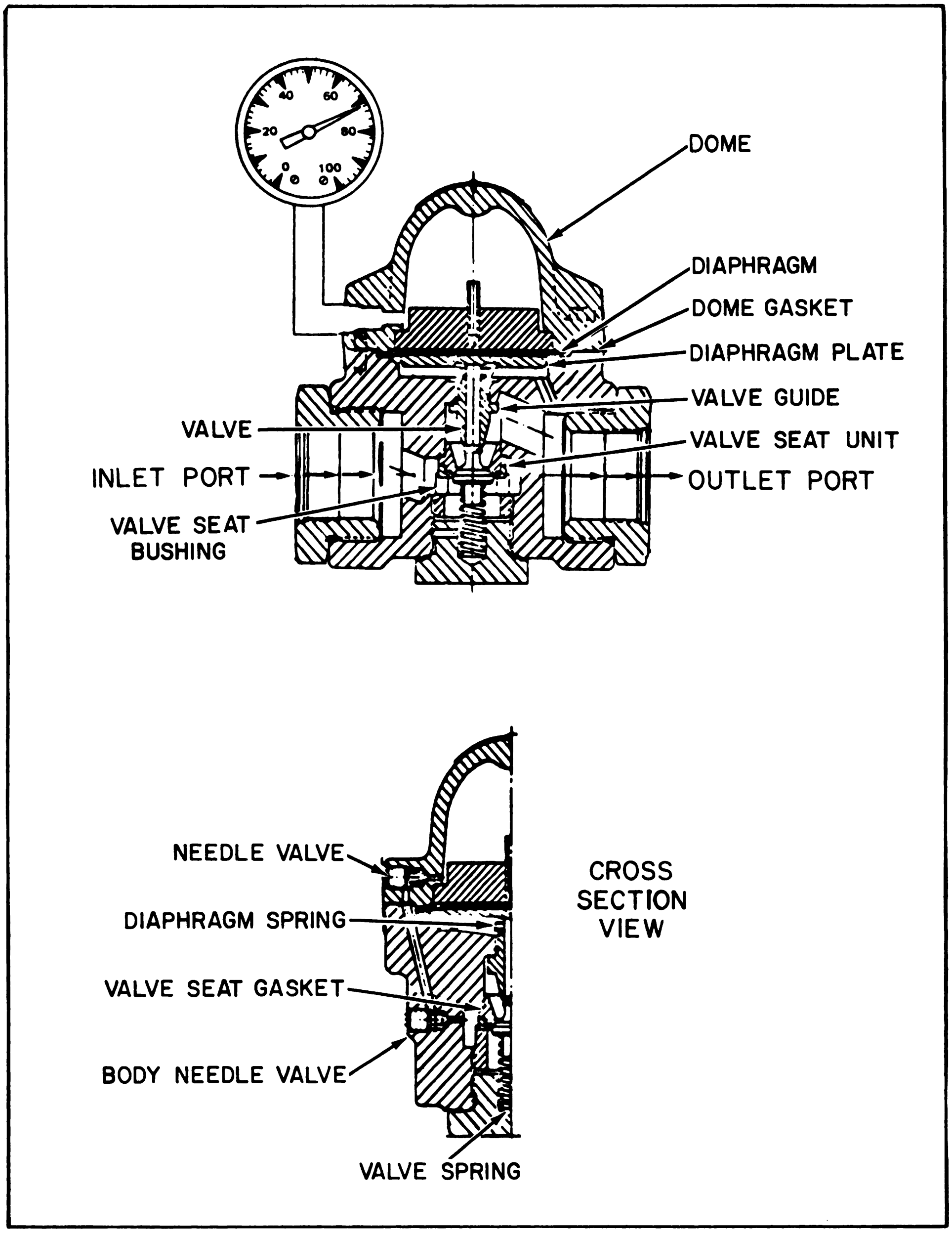

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Figure 6-32.—Pressure regulator.

the air dome. These two needle valves are used to seal off or trap air in the air dome at a pressure approximately equal to the desired outlet pressure. Since the air dome pressure is approximately equal to desired outlet pressure, a 0- to 100-psig meter is installed, which constantly monitors air dome pressure. This pressure is factory adjusted to 80 psig, which is the inlet pressure to the dehydrator unit.

Since the dome is sealed after loading, a change in temperature will cause a slight change in dome pressure, with a corresponding shift in outlet pressure. This outlet pressure shift amounts to about 1 psig for each 5 Fahrenheit degrees.

The pressure regulator is a balanced pressure regulator that is actuated by static gas pressure in a sealed dome. There is a flexible diaphragm between the sealed dome and the outlet line fluid. When outlet line pressure drops below dome pressure, the diaphragm moves out slightly and pushes the main valve open. This allows inlet line gas to flow through the valve until outlet line pressure builds up enough to balance the dome pressure. Then, the diaphragm moves back to throttle or closes the main valve so that dome and outlet pressures always remain in balance.

Any change in dome pressure causes a corresponding change in outlet line pressure. When the dome is completely vented, the main valve shuts off bubble tight.

Any trouble with the pressure regulator can usually be traced to the valve and valve seat, or to the diaphragm and O-rings being worn or deteriorated.

## Dehydrator

The dehydrator (fig. 6-33) consists of two desiccant chambers filled with desiccant in the

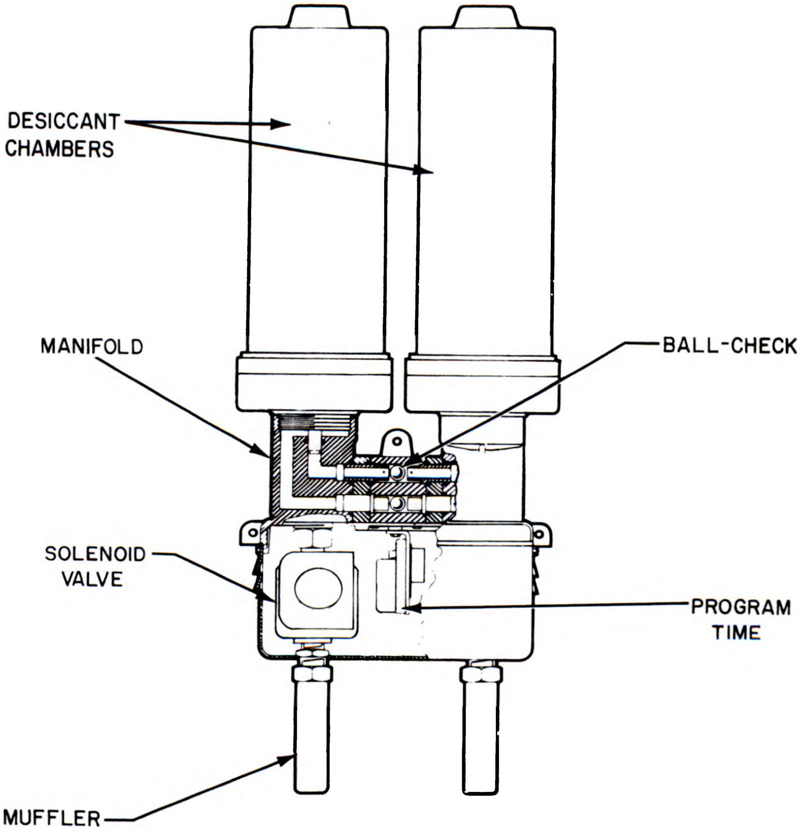

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Figure 6-33.—Dehydrator.

form of small spheres. The desiccant chambers are supported by the manifold, and they are connected to the manifold by internal air passages. A pair of two-way solenoid valves are attached to the bottom side of the manifold.

The program timer controls the operation of the two solenoid valves. In one 60-second period, each solenoid valve is open for 22 seconds and closed for 38 seconds. The timing for the solenoid valves is such that both valves are closed for two 8-second dwell phases. (Dwell will be explained later in this chapter.) One complete cycle takes place in each desiccant chamber every 60 seconds.

Dry air is needed for reactivation of the desiccant chambers. A small quantity of dry air (figs. 6-33 and 6-34, phase I) is bypassed around the ball-check valve by a fixed orifice (B) in the valve body for this purpose. It is expanded to atmospheric pressure through the fixed orifice, which controls the purge airflow. The purge air back flows to atmosphere through each desiccant chamber during half of each cycle. The dry purge air enters the top of the chamber. The oil and water that are removed from the chamber are discharged from the bottom of the chamber through the purge muffler.

The key to the simplicity and unusual efficiency of the dehydrator is its unique valving system. A particular point to notice is that the solenoid control valves handle only the purge air. (The main airflow through the unit does not pass through them as in older units employing three-way valves.) This means that simple, direct-acting, large-orifice, two-way valves can be used to eliminate the sources of high-pressure drops. In addition, this type of valve is more dependable.

Let us take a detailed look at the operation of a dehydrator. We'll consider a complete cycle of operation. Refer to figure 6-34, phases I, II, and III for the following descriptions.

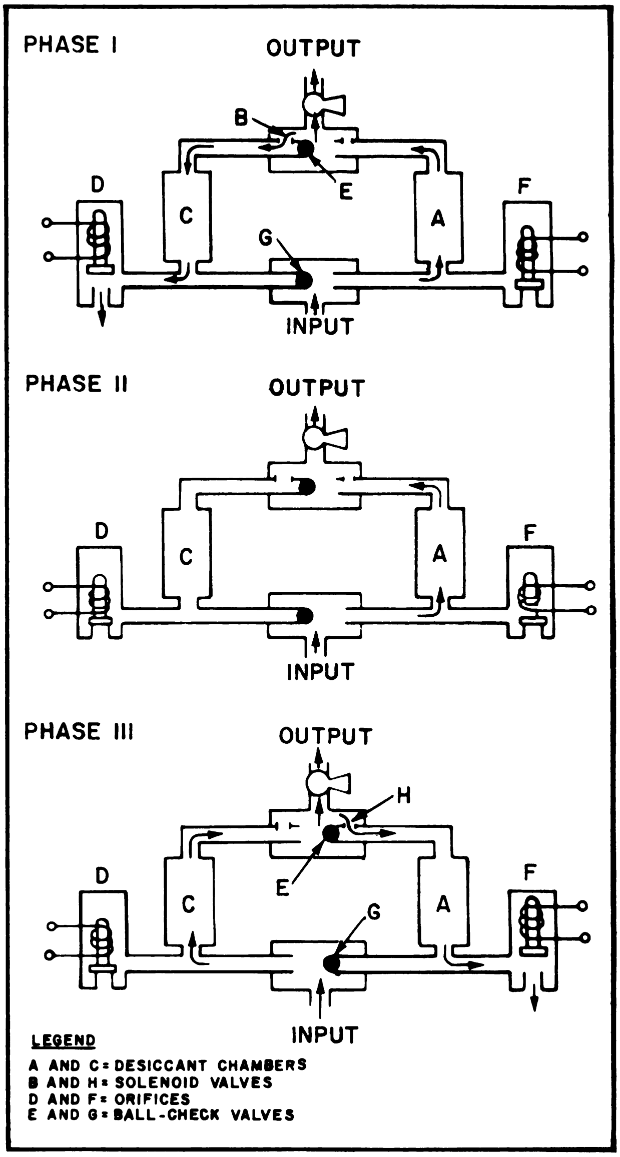

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Figure 6-34.—Dehydrator operating cycle.

**PHASE I—DRY/PURGE.**—The solenoid valve (F) is closed. Solenoid valve (D) is open. Incoming moist air, under pressure, flows through chamber (A), where it is dried. Most of this dry air is passed through the outlet conduit to be put to use. A small quantity, however, bypasses the closed ball-check valve (E) through a small orifice (B) into chamber (C). Here it picks up moisture from the partially saturated desiccant and passes out of the unit through the open valve (D). Since the chamber being purged is at near-atmospheric pressure, the ball-check valves (E) and (G) are held in place by the pressure of the main airflow.

**PHASE II—DWELL.**—The timer closes both solenoid valves (D) and (F). This allows the pressure in the regenerated chamber (C) to build up through the orifice to approximately that of chamber A.

**PHASE III—DRY/PURGE.**—In figure 6-34 (phase III), the solenoid valve (F) is opened by the timer; solenoid valve (D) remains closed. The pressure in chamber (A) drops immediately, causing the ball-check valves (E) and (G) to move rapidly to the right, sealing off chamber (A) and directing the main airflow through chamber (C) where it is dried. A portion of this dry air, leaking through orifice (H), passes through chamber (A) where it picks up moisture and is emitted to the atmosphere through valve (F). After completing another dwell period, the cycle repeats.

The most important single aspect of maintaining the dehydrator is to assure proper operation of the automatic dump traps on the fluid separator and the telltale oil filter units. If oil, water, and sludge are not expelled, the accumulated liquids may fill the trap, back up into the air lines, and pass into the dehydrator. Complete failure of the desiccant material of the dehydrator to dry and purify quickly follows. If this happens, you will have to completely disassemble and clean the fluid separator, telltale oil filter, both dump traps, the pressure regulator, the dehydrator, and all the interconnecting piping. Also, the desiccant in the dehydrator chambers will have to be replaced.

### Dust Filter

The dust filter (fig. 6-29) consists of a separable housing, which contains a replaceable filter cartridge, constructed of pleated paper (5 microns). The design is such that air flows from the outer (housing) side inward to a hollow center that is connected to the outlet port. Dust is then collected on the outer surface of the filter cartridge. Since the collected dust is dry, any substantial accumulation falls to the bottom of the housing and lessens the possibility of clogging the filter.

### Flow Limiter

A flow limiter (fig. 6-29) is installed between the dust filter and output of the dryer. It is designed to limit the output of the dryer, should the output of air increase beyond the limits of the dryer capability.

The flow limiter is a spring-restrained poppet valve with an orifice in the poppet valve. The poppet valve offers no appreciable resistance to the flow of air during normal operation. When the flow exceeds the design of the dryer, the poppet valve closes, and the flow is then limited by the orifice in the poppet valve.

## MOISTURE MONITOR

A moisture monitor probe is installed downstream from the dryer to monitor the dew point of the dry air. The monitor gives you a visual reading in ppm (parts per million) or in dew point (for example, −40 °F). Most monitors have a built-in alarm system. It provides both audible and visual alarms when the air quality is less than the value that it is set to.

When the monitor unit is designed to read the moisture content of the air in dew point, a conversion chart is included with the unit. This chart converts the individual reading to a standard dew-point reading, which is at atmospheric pressure; for example, a dryer feeding three waveguide systems at 10, 20, and 30 psig. You take a reading of the dew point on the three different waveguide systems and come up with −32°, −25°, and −21 °F, respectively. Is the last reading of −21 °F a good reading? The radar equipment manual specified −25 °F as the minimum requirement (at atmospheric pressure). Using the dew-point conversion chart, all three of the above readings convert to −40 °F, which is well within tolerance for the radar. The conversion chart is used to convert the individual dew-point reading at various pressures to a known standard.

The sensor probe, which is used to monitor the dry air, consists of an aluminum strip that is anodized by a special process to provide a porous oxide layer. A very thin coating of gold is evaporated over this structure. The aluminum base and the gold layer form the two electrodes of what is essentially an aluminum oxide capacitor. Water vapor is rapidly transported through the gold layer and equilibrates (is in equilibrium) on the pore walls in a manner functionally related to the vapor pressure of water in the atmosphere surrounding the sensor.

The number of water molecules absorbed on the oxide structure determines the conductivity of the pore wall. Each value of pore wall resistance provides a distinct value of electrical impedance, which, in turn, is a direct measure of water vapor pressure.

The monitor unit, as we have indicated, is usually a complex impedance meter. It applies a low-frequency signal of less than 100 Hz to the sensor probe. By measuring the change in this signal amplitude and phase, caused by the sensor probe, the monitor unit continuously computes the impedance of the probe and then displays the value on the unit's meter as the dew point.

Most moisture monitors do not require routine maintenance. If a malfunction should occur, you should isolate the problem by substituting a sensor probe (known to be good). (The sensor is extremely fragile and nothing should touch the aluminum oxide element.) If the problem is isolated to the monitor unit and not the sensor probe, you should use the unit's schematic diagrams and a multimeter to isolate the problem.

## WAVEGUIDE FLOODING

An improperly maintained liquid cooling system can cause a major disaster in your waveguide system. The damage caused by waveguide flooding can easily run into thousands of dollars and include the expenditure of hundreds of man-hours by ship's force.

Various components of high-powered radars, such as dummy loads for radar silence operation and load isolators, are cooled by the use of liquid coolant. These components use a Teflon® or ceramic plug (or disk) in a water-cooled load. Transmitted rf energy passes through the plug and is absorbed as heat by liquid coolant flowing through the load. The plug acts as a window for rf energy, and at the same time, forms a watertight seal between the waveguide and the coolant jacket of the load.

Particles of oxidation and dirt from a dirty coolant system can buildup on the coolant side of the Teflon® plug. The buildup can create an impedance mismatch or hot spot. This condition can generate an arc, which carbonizes the Teflon® plug so that coolant can leak through or around the carbonized plug.

Since a nominal 80-psig pressure differential exists between the coolant in the load and air in the waveguide, coolant can flow from the water load into the waveguide, resulting in waveguide flooding.

Once the coolant has entered the waveguide, it can flow through the various sections of the waveguide system. It can cross over to other waveguide systems through the common dry air lines that are connected to waveguide. As you can see from the above description, if the coolant leak is severe or remains undetected for a long period of time, a leaking water load can completely fill the waveguide system with coolant.

You have to follow a logical troubleshooting procedure. If the problem is a common one in a specific weapon system, there will probably be a technical bulletin issued that describes how to isolate the flooding damage. The following is a condensed procedure to follow for waveguide flooding.

### Isolate Extent of Flooding

It is imperative that the amount of waveguide contamination be determined before the microwave system is drained of water. If the exact level of contamination is not determined, many microwave components may needlessly be removed and many man-hours expended. You will have to secure the cooling system and close all valves to the effected areas of the radar. If the cooling system uses a pressurized expansion tank, you will have to bleed off the air pressure. If you can still see the coolant in the sight glass of the expansion tank, you can estimate the amount of coolant missing since the system was last filled. Use the estimated loss to determine the amount of contamination that may have occurred. The dry-air system should be secured and all valves closed to prevent movement of this coolant.

You should start at the highest point in the waveguide system and work down to the flooded area of the waveguide. By proper isolation of the flooded waveguide, the extent of repairs can be minimized. Ensure that you do not have trapped coolant in the dry-air lines. Electrical power should be secured and tagged out to prevent a shock hazard because of water that has spilled.

### Clean-Up Procedure

First drain the contaminated waveguide by opening the waveguide at convenient points. Next, remove the components to a clean work area, being careful not to damage them. You should mark each piece to indicate its location and position so that it can be properly reinstalled.

Each section of waveguide has to be cleaned by scrubbing it inside and out with hot soapy water. Long sections of waveguide can be cleaned by pulling a clean lint-free rag through each section. A soft cotton cord (not waxed lacing cord) can be used to accomplish this. The rag should be pulled through each section in both directions. You must use extreme care to avoid damage to such things as attenuator vanes (thin glass) or termination load pieces inside the waveguide components.

Some waveguide components are epoxyed together, and it may not be possible to disassemble them. After cleaning components of this type with hot soapy water, rinse each piece with hot fresh water and then with hot distilled water. Dry each component, and then inspect the interior for damage with a very bright light. (Do NOT use a flashlight because it is not bright enough.) In some cases, the removal, installation, and calibration of balanced waveguide runs in the antenna are considered beyond ship's force capability. This is because of the special tools and test equipment required.

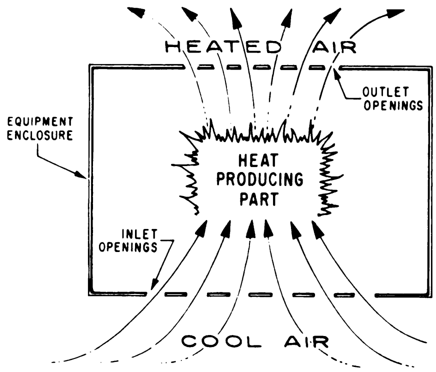
The waveguide should be reassembled with new gaskets. Also, all damaged or broken components should be replaced. Purge all air lines before reconnecting to the waveguide. After assembly, the waveguide should be purged with dry air for several hours. This is done before the use of the waveguide to ensure the removal of all moisture.

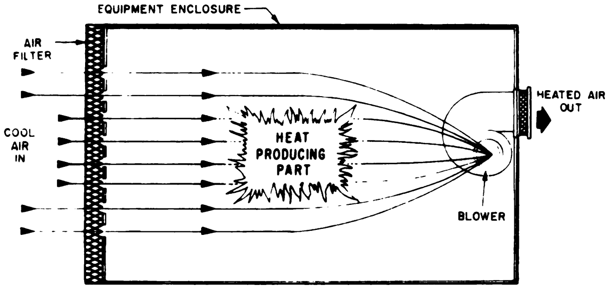
Also, before the use of waveguides, you should inspect other water-cooled components for possible deterioration. By completing this step, you can prevent a reoccurrence of waveguide flooding caused by oxidation or dirt buildup on the coolant side of the high-power components.

## SUMMARY

In this chapter, you have been introduced to the various types of cooling systems for electronic equipment. You have studied the function and operation of major components within the liquid cooling system. You were also introduced to a typical waveguide dry air system and its major components. These topics have provided you with the fundamental knowledge of their operation so that after some hands-on training you can maintain them with confidence. The following is a summary of specific points within the chapter.

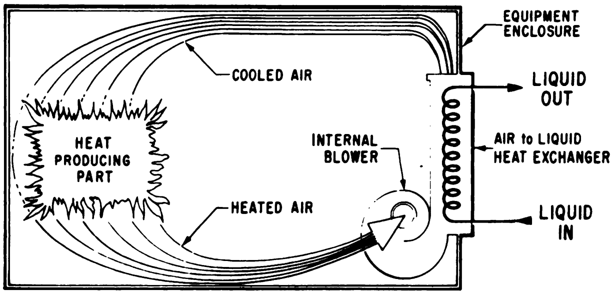
CONVECTION COOLING takes place as the air in the vicinity of a hot component is warmed and then rises to be (fig. 6-1) replaced by cool air.





FORCED AIR COOLING uses a blower to provide movement of the air past the heat producing part.

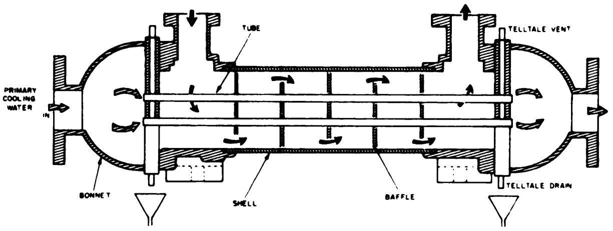
AIR-TO-AIR COOLING is used on hermetically sealed equipment. An air-to-air heat exchanger is used to transfer the heat from the equipment's interior to its exterior.



AIR-TO-LIQUID COOLING uses a heat exchanger with a circulating liquid to remove heat.

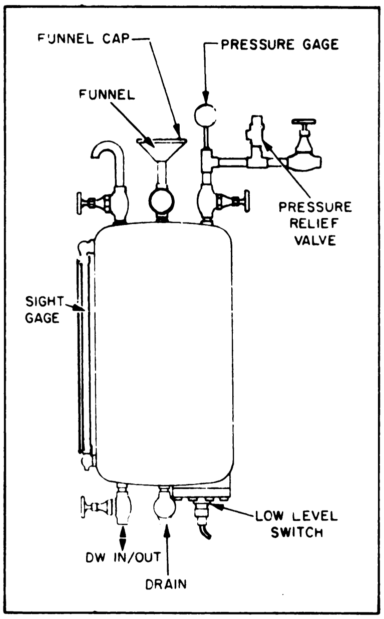
LIQUID COOLING SYSTEM is composed of two basic cooling systems. The primary system provides the initial source of cooling water. The secondary system transfers the heat load from electronics equipment to the primary system by way of a heat exchanger.

THREE BASIC CONFIGURATIONS of a liquid cooling system are used in the U.S. Navy. Type I uses a SW/DW heat exchanger with a SW/DW heat exchanger in standby. Type II uses a SW/DW heat exchanger with a CW/DW heat exchanger in standby. Type III uses a CW/DW heat exchanger with a CW/DW heat exchanger in standby.



HEAT EXCHANGERS are used to transfer heat from secondary cooling systems to primary cooling systems. Secondary coolant flows through the shell while primary coolant flows through the tubes. A single-pass heat exchanger (shown) is more efficient than a double-pass heat exchanger.

EXPANSION TANKS perform three important functions: maintains a positive pressure on circulating pump; compensates for expansion/contraction of the coolant caused by temperature changes; vents air from the system and provides a source of makeup water. A gravity expansion tank is located at the highest point in the secondary system. The pressure expansion tank (shown) is located near the circulating pumps and is pressurized with air.

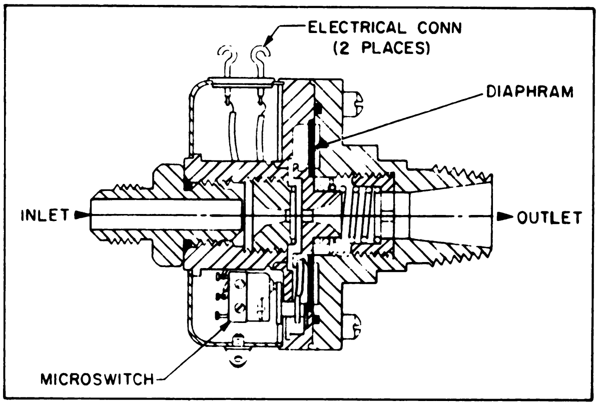


SEAWATER STRAINERS are used to remove debris from the seawater that could clog the heat exchanger tubes.

TEMPERATURE REGULATING VALVES regulate the temperature of the secondary cooling system by controlling the flow of coolant to the heat exchanger.

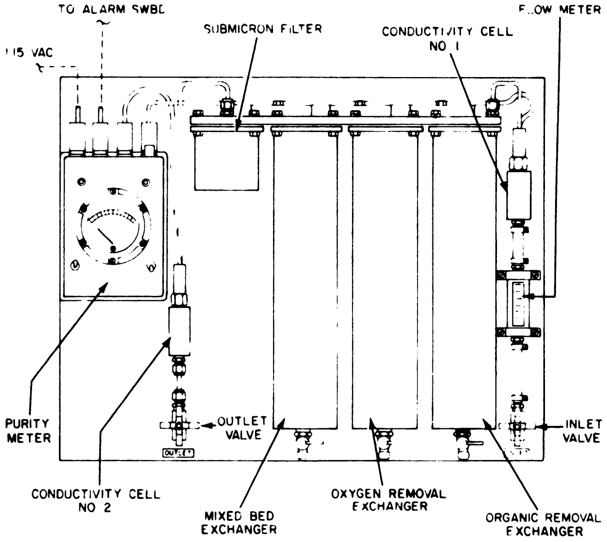
FLOW REGULATION is used to reduce the flow of coolant in both primary and secondary sytems.

FLOW MONITORING DEVICES are used to monitor the flow of coolant.



CIRCULATING PUMP is used to move the coolant in the secondary cooling system. Each cooling system uses two pumps, with one being kept in standby.

THE DEMINERALIZER is used to maintain the secondary coolant in an ultrapure state to minimize corrosion and the formation of scale. The coolant is purified by organic compound adsorption, oxygen removal, and an ion exchange process cartridge. Water purity is measured by a purity meter and is displayed as resistivity or conductivity.



THE OXYGEN ANALYZER is used to measure the amount of dissolved oxygen in the secondary cooling system.

THE COOLANT ALARM SWITCHBOARD is used to monitor the overall condition of the cooling system and provide a visual and audible alarm to indicate a fault condition.

DRY AIR is used primarily in the waveguide to prevent rf energy from arcing in the waveguide.

THE SHIP'S CENTRAL DRY AIR SYSTEM is the primary source of dry air for electronic equipment. A dehydrator is used to remove the moisture from the compressed air.

DEW POINT is the temperature at which water vapor begins to deposit as a liquid, and it is stated in reference to atmospheric pressure. The lower the dew-point number, the dryer the air.

THE AIR DRYER is used to remove both oil and water from the air with a continuous output of dry air.

THE FLUID SEPARATOR uses centrifugal force to extract droplets of liquid from the air.

THE TELLTALE OIL FILTER is used to remove oil from the air by absorption. The amount of oil in the filter is indicated by the amount of dark red absorbing material visible in the filter.

THE DESICCANT DEHYDRATOR removes moisture and oil vapor by adsorption. One desiccant chamber removes contaminates from the air, while the other chamber is being purged.

THE MOISTURE MONITOR is an electronic unit used to measure the quality of dry air, and display it in ppm or degrees Fahrenheit or Celsius (dew point).

# CHAPTER 7

# BATTERY ALIGNMENT

Battery alignment is the process of adjusting all the elements of a weapons system (including all gun bores, missile launchers, fire control directors, radar antennas, optics, and gyrocompasses) to common reference points, lines, and planes, and maintaining them in this relationship. Battery alignment is a critical factor in the fighting effectiveness of any combat ship. Without proper battery alignment, in general, the data exchanged between elements of the weapons system would be erroneous. This could possibly result in increased target acquisition times, incorrect stabilization, projectiles not impacting on target, or missiles not acquiring the target or capturing the guidance radar beam.

The battery alignment of a ship is accomplished by two distinct procedures—original alignment (dry dock alignment) and alignment afloat. *Original alignment* is the initial alignment made in a fire control and weapons system at the time of original construction and installation. This is an elaborate and a highly accurate series of operations, done in dry dock by the shipbuilder or outfitting yard. Original alignment is also performed whenever a new or modified major weapons system is installed. A check of this alignment is made when the ship is in dry dock for repairs.

Battery alignment in dry dock is usually performed by shipyard ordnance mechanics. You will not be directly involved with the work that is performed by these personnel. For this reason, shipyard battery alignment is not discussed in this chapter. If you desire information, consult the latest revision of *Theory of Combat System Alignment* (OP 762).

*Alignment afloat* refers to alignment operations performed while the ship is waterborne (in port or underway). Alignment afloat requires standards of accuracy just as high as those of original alignment. The main difference is that alignment afloat is performed by the weapons department personnel with equipment available on the ship.

## ALIGNMENT CONCEPTS

Alignment is based on the concepts of parallel lines, parallel planes, and a geometric coordinate system. Parallel lines (fig. 7-1, view A) are defined

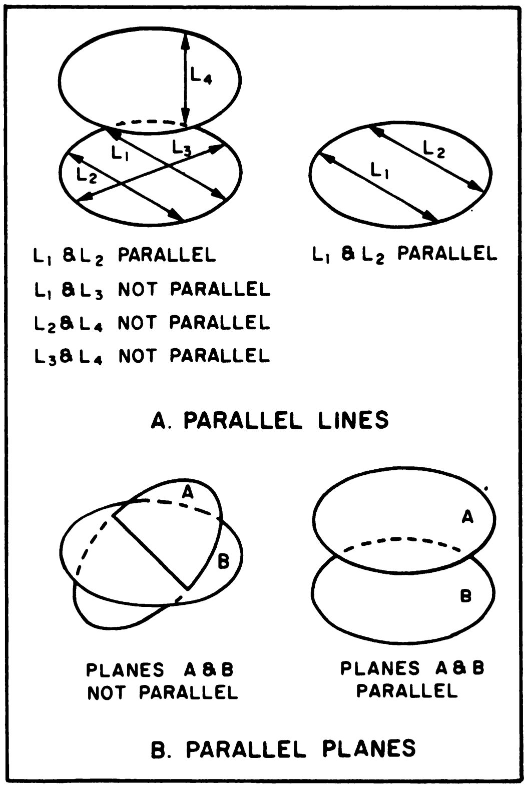


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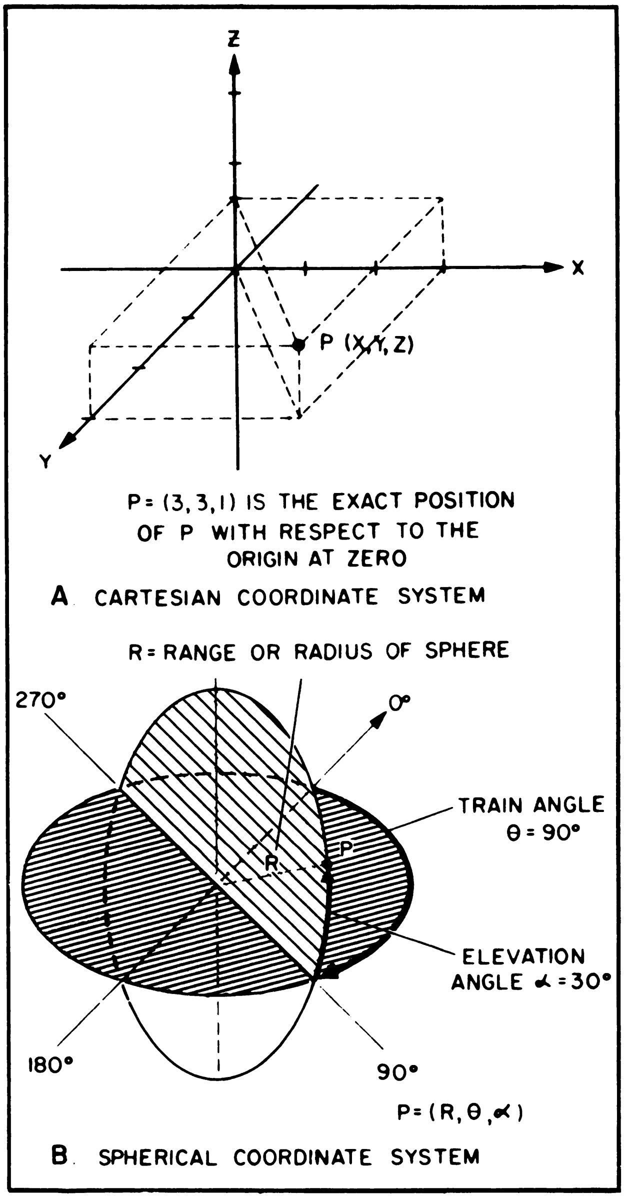
Figure 7-1.—Typical examples of parallel lines and planes.

as lines in the same plane that, when extended indefinitely, do not intersect. *Parallel planes* (fig. 7-1, view B) are defined as planes that do not intersect. A geometric coordinate system provides a method for determining the position of a point, line, curve, or plane in a space of given dimensions (reference frame). Examples of geometric coordinate systems are the cartesian and the spherical coordinate systems, shown in figure 7-2.


Z
X
Y
P (X,Y,Z)
P= (3,3,1) IS THE EXACT POSITION OF P WITH RESPECT TO THE ORIGIN AT ZERO
A CARTESIAN COORDINATE SYSTEM
R= RANGE OR RADIUS OF SPHERE
270°
0°
TRAIN ANGLE θ = 90°
P
R
ELEVATION ANGLE α = 30°
180°
90°
P= (R, θ, α)
B SPHERICAL COORDINATE SYSTEM

55.350

Figure 7-2.—Cartesian and spherical coordinate systems.

Ultimately, the alignment of parallel lines, parallel planes, and coordinate systems is used to establish a pointing line for each piece of equipment in the ship's combat system. The line representing the direction in which a piece of equipment is pointing is referred to as the *pointing line* of that equipment. As previously indicated, the pointing line may be the bore axis of a gun, the line of sight of a director, or the propagation axis of a radar beam. Accurate alignment is not possible unless the pointing line is precisely determined.

## FRAME OF REFERENCE

The reference point, reference direction, and reference plane form a geometric structure called a *reference frame* (fig. 7-3). In the complete reference frame, directions are specified by two angles (train and elevation) measured about the reference point.

A geometric measurement is based on a definite and complete set of geometric references. To permit clear and accurate definition of target position, a definite point on the ship (such as a director) is selected as the starting point for the measurement. As a reference point, a director center of rotation is selected arbitrarily because the director has interface with all the major

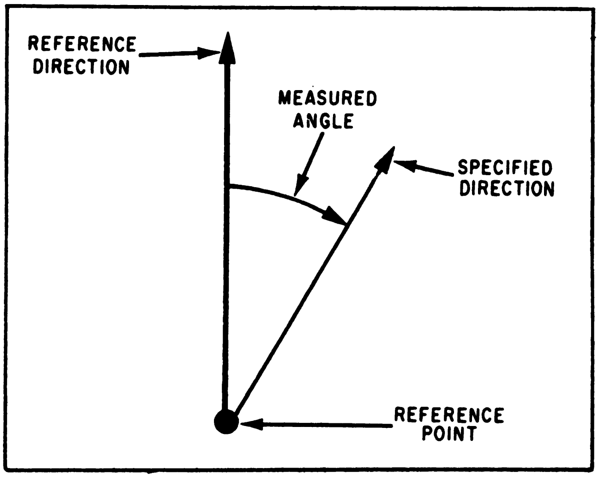


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Figure 7-3.—Measurement of an angle from a reference direction.

equipment of a battery. Once the reference point is determined, it becomes a part of any measurement made from it and must be clearly specified before subsequent measurements have any meaning.

Once the reference point is selected, a reference direction is established from which train angles are measured. *Train angles* are measured about the reference point, beginning at the reference direction, as shown in figure 7-3. In naval combat systems the ship's centerline, which points in the direction of the bow, is used as the reference direction.

Angles expressing direction cannot be described unless a means is available for specifying the plane in which the angle is to be measured. This plane (fig. 7-4) is referred to as the reference plane and may be any plane convenient for use. The horizontal plane is one of the most commonly used reference planes because of the ease of using a spirit level or similar device to determine the plane. In naval combat systems, the reference plane is parallel to the reference element (director) roller path. Whichever plane is selected for reference, it must be clearly specified before subsequent measurements are of any significance. When the reference plane is used, a means must be established to denote the top of the plane to express the angle correctly. Train angles are measured clockwise from the reference direction on the top of the plane.

The elevation angle is in a plane perpendicular to the horizontal reference plane and is measured from the reference plane, as shown in figure 7-5. The concept of a reference frame is important in the expression of a direction and the problems related to alignment. It must be remembered that the reference point is a definite point aboard ship, and the reference plane and reference direction have a definite orientation in respect to the reference point.

In fire control, it is often necessary to operate simultaneously with two or more reference frames. (For instance, these frames might be situated in different parts of a ship.) It may be desirable to measure target data with several directors because of a need for flexibility in controlling different fire control systems to obtain a wide range of view, or in case one director is out of commission. In such an event, we must be able to use the target data from either of the directors to get a fire control solution.

To interpret data measured in different frames, we must know how the frames are situated with respect to each other. The difference or displacement between two frames may be of two kinds—linear and angular.

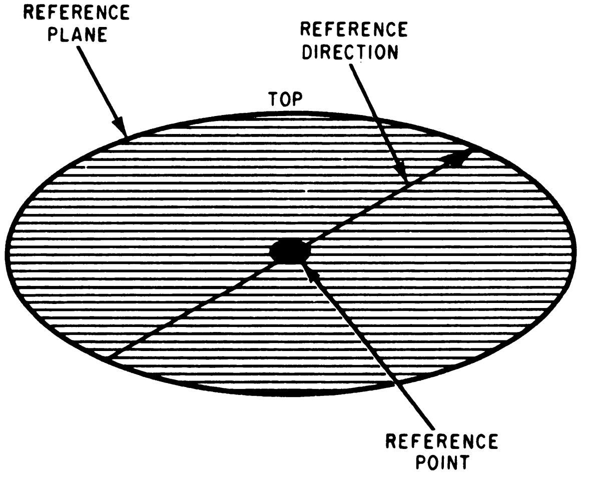

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**Figure 7-4.—Typical reference plane.**

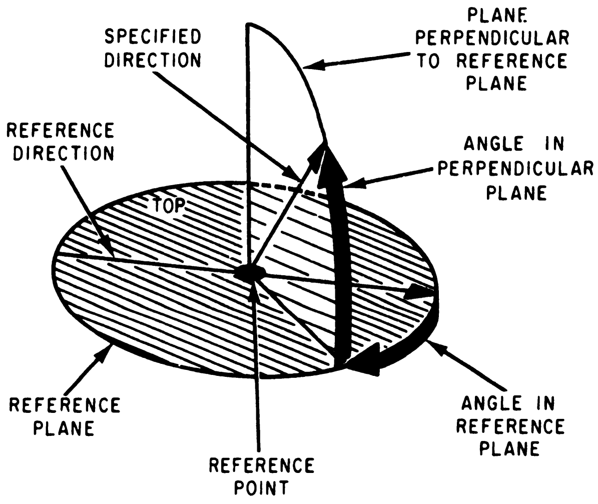

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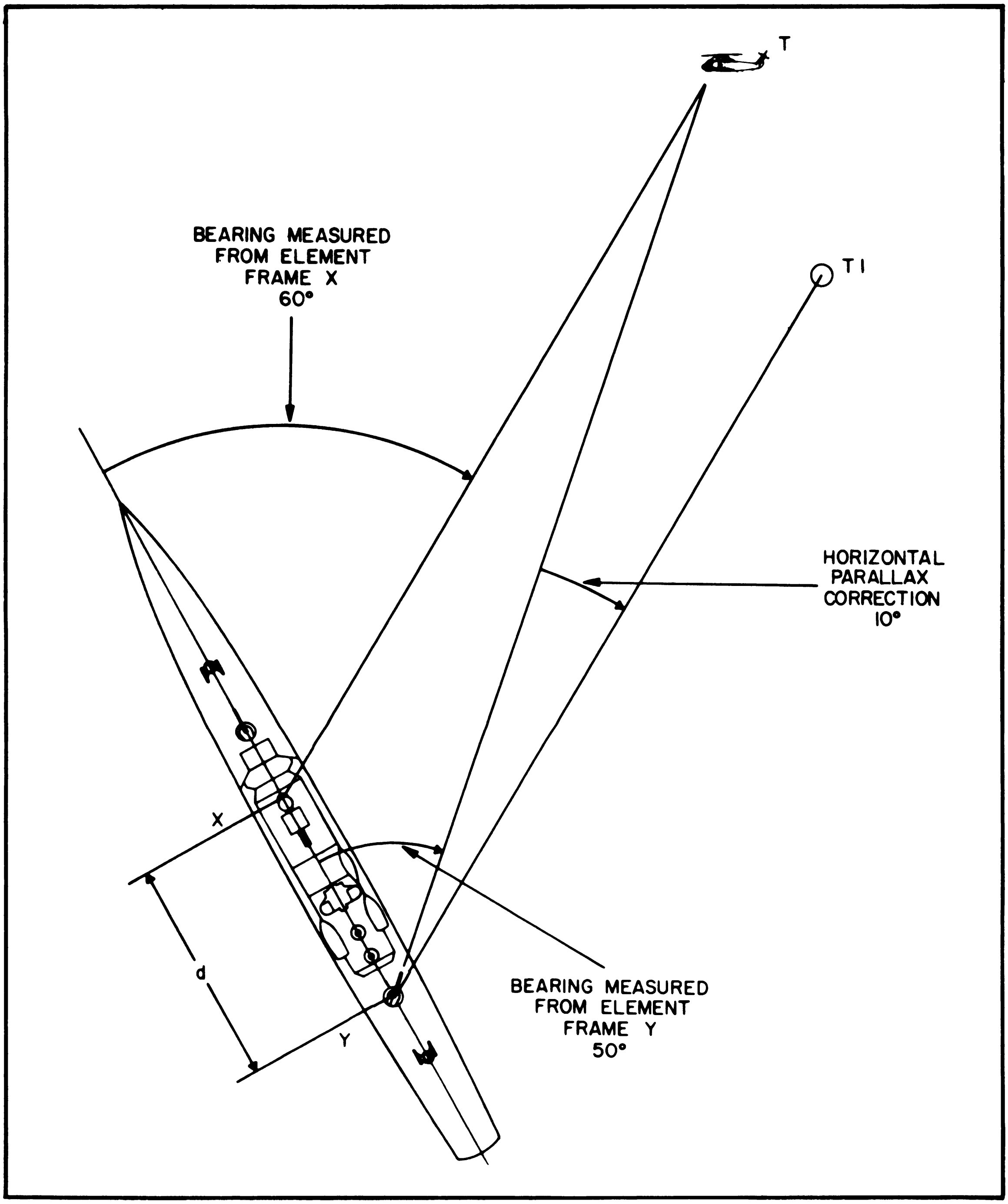
**Figure 7-5.—Representation of a complete reference frame.**


T
BEARING MEASURED FROM ELEMENT FRAME X 60°
T1
HORIZONTAL PARALLAX CORRECTION 10°
X
d
Y
BEARING MEASURED FROM ELEMENT FRAME Y 50°

55.354

Figure 7-6.—Parallax resulting from linear displacement of two frames.

## LINEAR DISPLACEMENT

Linear displacement is the distance between two reference frames measured between their reference points. This displacement may be in the vertical direction, the horizontal direction, or both.

The corrections made necessary by the linear displacement between the reference points are called *parallax corrections* and are considered separately from corrections arising from the rotation between the frames. Parallax corrections can be separated into either dynamic parallax corrections or static parallax corrections.

### Dynamic Parallax

Position quantities computed for the reference frame are correct only for equipment located exactly at the reference point. Dynamic differences result because the motion of equipment not located at the reference point is different from the motion of equipment located at the reference point because of the rolling and pitching of the ship. These dynamic factors are usually negligible and are not normally corrected for.

### Static Parallax

Static parallax is caused by the linear and angular displacements between the reference point and equipment located elsewhere on the ship. Figure 7-6 shows two parallel reference frames, X and Y, displaced from each other by the distance d. Frame X is the standard reference frame. The bearing of target T, as determined from reference frame X, is 60°. If this is applied in a reference frame at Y, the line YT is determined. This line is parallel to XT but does not pass through the target because of the displacement d between the reference frames. To cause the line from Y to pass through the target in this example, a parallax correction angle of 10° must be subtracted from the bearing value measured for frame X.

Elevation angles also are affected by displacements between reference frames. If elevation angles measured in one frame are to be used in another frame, they must first be corrected for parallax. The magnitudes of parallax corrections in train and elevation vary considerably with target bearing, elevation, and range, and the magnitude and orientation of the distance between the reference frames.

The basic point to remember is that whenever two reference frames are displaced from each other, data measured from one frame are, in general, not equal to data measured from the other frame. If the differences are significant, data measured in one frame must be corrected for parallax before it is applied in other frames.

## ANGULAR DISPLACEMENT

Corrections arising from reference directions or reference planes not being parallel are rotation corrections. If the reference lines are both in a plane that is perpendicular to both reference planes, as shown in figure 7-7, but the reference planes are not parallel, the bearing angles and elevation angles are different.

When the angle between the reference planes is relatively small, the major difference is in the elevation angles; the difference in the bearing angles is usually small enough to be ignored. The latter case is important in the alignment of a combat system.

## ALIGNMENT EQUIPMENT

Alignment equipment is used by shipboard and shipyard personnel to align the system elements. Generally, combat system alignment checks and adjustments are accomplished with test equipment and tools normally found aboard ship. Because of required combat system accuracy, however, special-purpose instruments are sometimes required for adjustments. This section will provide you with a brief description of the most commonly used alignment equipment.

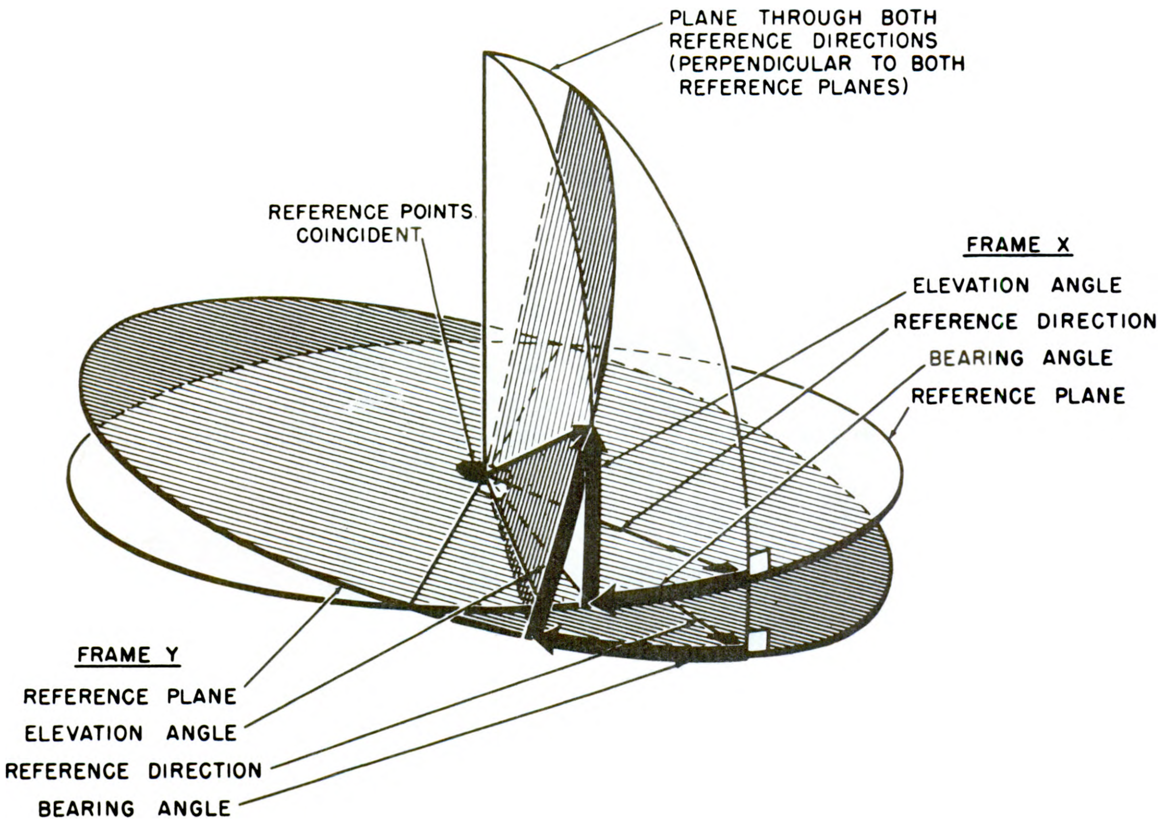


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**Figure 7-7.—Rotational corrections between unparallel planes.**

## TRANSITS

A transit is an optical-surveying instrument that is used for measuring angles. A typical transit is shown in figure 7-8. Essentially, the transit provides an optical line of sight (LOS) that is perpendicular to, and supported on, a horizontal axis. The horizontal axis is perpendicular to a vertical axis about which it can rotate. Spirit levels are used to make the vertical axis coincide with the direction of gravity. Graduated circles with verniers are used to read the angles.

### Transit LOS

The LOS of the transit is the telescope, which is mounted with two rotational axes, horizontal and vertical. The position of the telescope LOS is measured by a bearing scale (horizontal circle) and an elevation scale (vertical circle). Both scales of the transit shown are provided with verniers that may be read to 1 ′ of arc, although some may be read to 20″ of arc.

### Leveling Screws

Leveling screws and spirit levels are provided so that the transit can be accurately adjusted to measure bearing angles in the horizontal plane and elevation angles in the vertical plane. The transit, which is mounted on an adjustable tripod, is portable so that it can be set up at any desired location.

## THEODOLITE

Theodolites are similar to transits, but they are normally more precise instruments. An example of a theodolite is shown in figure 7-9. Theodolites, which employ micrometer microscopes that are

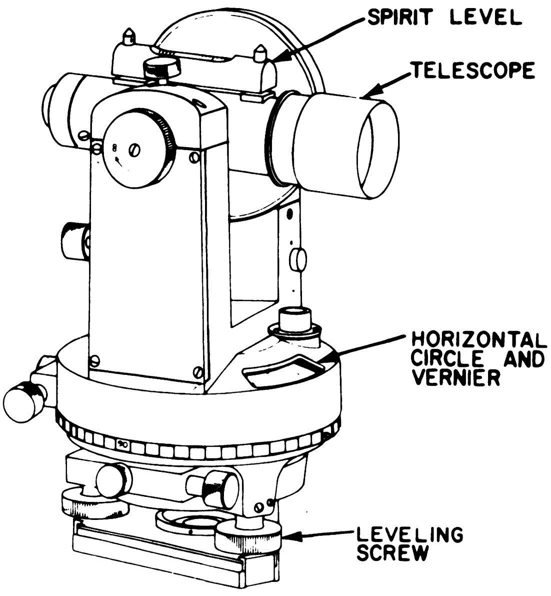

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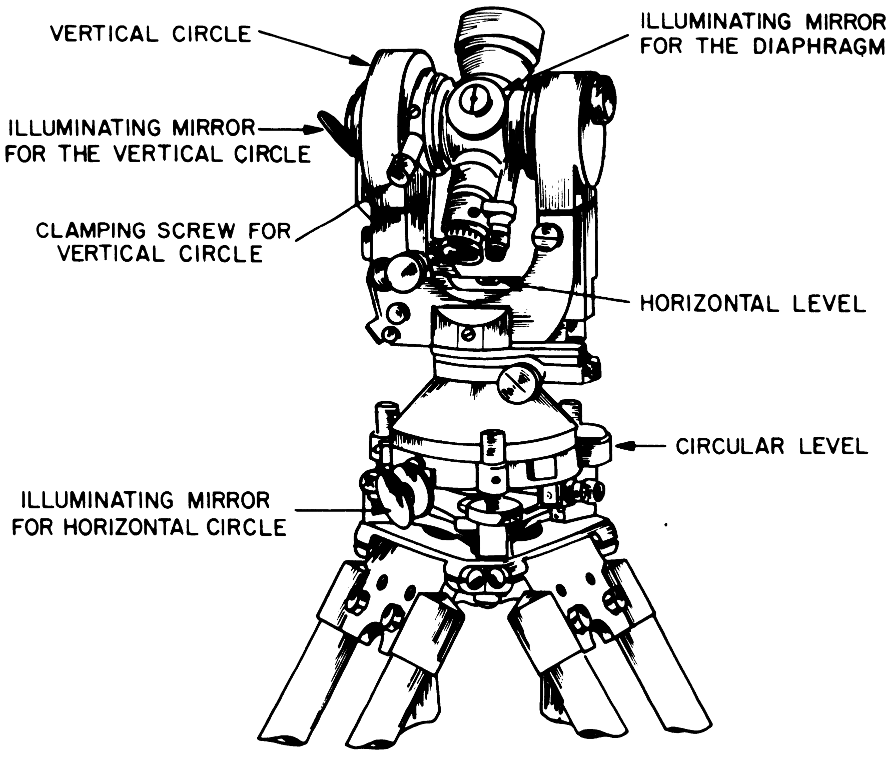
**Figure 7-8.—A typical transit.**

especially designed for rapid and accurate readings, are used to read the graduated vertical (for elevation) and horizontal (for train) circles.

Micrometer microscopes create such precision that the accuracy of the optical reading device is governed by the circle and not by the way the circle is read. Different types of theodolites can be read directly to 10″, 1″, or 0.1″ of arc.

## CLINOMETERS

A clinometer is an instrument used for measuring inclinations in the horizontal plane. Clinometers are used in naval shipyards principally to measure inclinations in equipment foundations and equipment roller path inclinations (RPI). All clinometers use a spirit level for indicating the true horizon and have some means


VERTICAL CIRCLE
ILLUMINATING MIRROR FOR THE DIAPHRAGM
ILLUMINATING MIRROR FOR THE VERTICAL CIRCLE
CLAMPING SCREW FOR VERTICAL CIRCLE
HORIZONTAL LEVEL
CIRCULAR LEVEL
ILLUMINATING MIRROR FOR HORIZONTAL CIRCLE

55.357

**Figure 7-9.—A typical theodolite.**

of measuring inclinations of the base with respect to the horizontal (spirit level).

Figure 7-10 shows the type of clinometer commonly used for making accurate roller-path-inclination measurements. The micrometer drum 90° clinometer is read directly to 1′ and can be interpolated to within 15″ on the drum. The 6-inch base length makes this type of clinometer suitable for many uses. An adjustable base permits reading angles from zero, even when working surfaces are not perfectly horizontal.

## Graduated Drum

Whole degrees are read through the observation port; minutes are read on the graduated micrometer drum. The compensation feature permits reading or setting negative and positive angles when working from surfaces not perfectly horizontal. The hardened steel base has a flat surface with a V-shaped groove that allows the level to be mounted on flat surfaces or cylindrical objects.

When turned, the graduated drum (60 divisions) moves the graduated arc (0° to 90°) 1° for each revolution. Pressing down on the drum knob disengages the worm and permits the setting knob of the level vial to be quickly, but only approximately, positioned. Turning the micrometer drum screw knob levels the vial or sets the angle exactly.

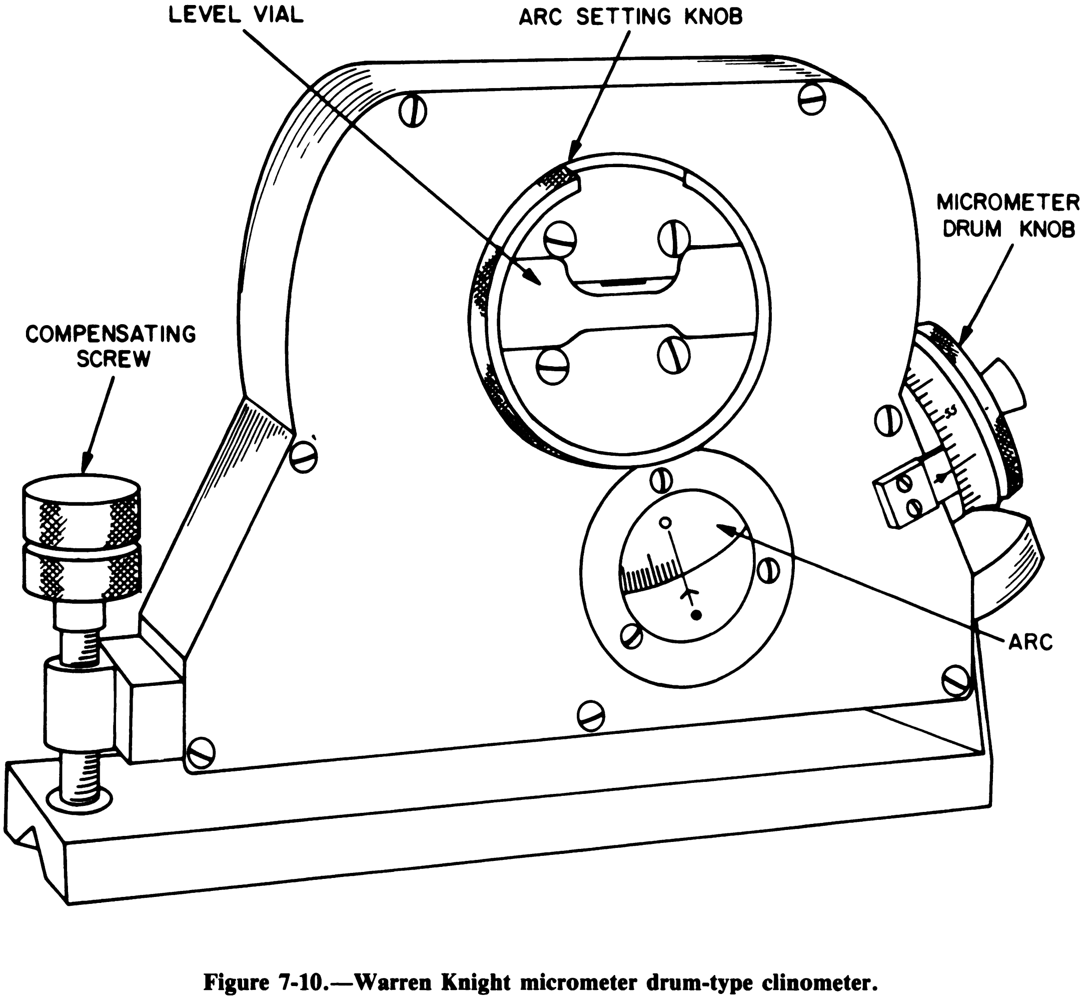


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Figure 7-10.—Warren Knight micrometer drum-type clinometer.

**Clinometer Mounting and Care**

When preparing to use a clinometer, you should ensure the clinometer is mounted on a clean and smooth surface. The clinometer should be clamped or sealed firmly to the surface, but not so tightly that it may become distorted. Damage to the clinometer is avoided through careful handling. Care should be used when using the clinometer in conditions of extreme temperatures. The clinometer is calibrated at an average temperature, and the size of the bubble changes with extremes causing error in the readings.

## GUNNER'S QUADRANT

A gunner's quadrant is similar to a carpenter's level, but it is more precise. It consists of a base with an arc mounted on it; this arc is perpendicular to the base (fig. 7-11). The arc is graduated in degrees and the drum in fractions of degrees.

To measure tilt, the gunner's quadrant is mounted on a horizontal surface of the element being measured, pivot end forward (toward the pointing line of the element). The arm with the bubble tube is pivoted until the bubble is

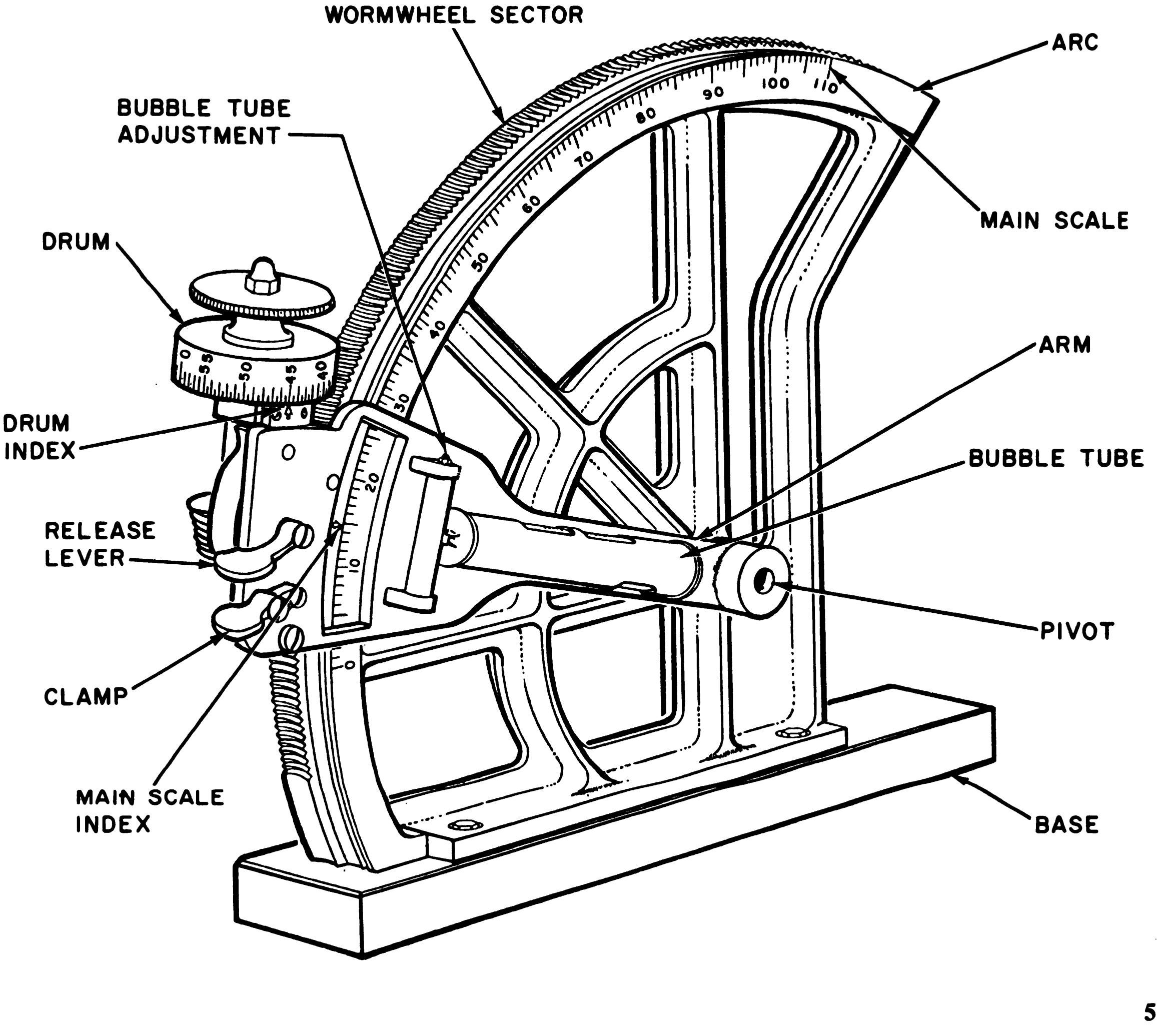

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Figure 7-11.—Gunner's quadrant.

approximately level. Next, the drum is rotated (screwed) until the bubble is precisely level. The main scale index indicates the degree of tilt of the element being checked, and the drum and drum index indicates any additional fractions of a degree.

## LEVELS

The two types of levels are (1) those that indicate entirely by means of graduations on the level vial and (2) adjustable levels that are hinged at one end and provided with calibrated micrometer adjustments at the other end to extend the range beyond that on the level vial alone.

### Hilger and Watts TB4

The Hilger and Watts TB4, figure 7-12, is an 8-inch adjustable block level that is calibrated to measure small tilts in either direction from the horizontal. It has a flat reference face with a V-shaped groove that allows the level to be mounted on cylindrical objects as well as on flat surfaces. A small bubble level is built-in for rough leveling perpendicular to the main level direction. The micrometer division is in minutes of arc and can be interpolated to within 15″ of arc.

### Sine Bar

Figure 7-13 shows a sine bar type of level. A sine bar uses a screw to raise and lower one end of the bar on which the spirit level is fixed. A dial mounted on the screw and a scale attached to the spirit level are used to read the inclination of the base. The mounting and care of levels are the same as for a clinometer.

## ALIGNMENT SIGHTS

Alignment sights are used to establish the pointing line of equipment. The pointing line may

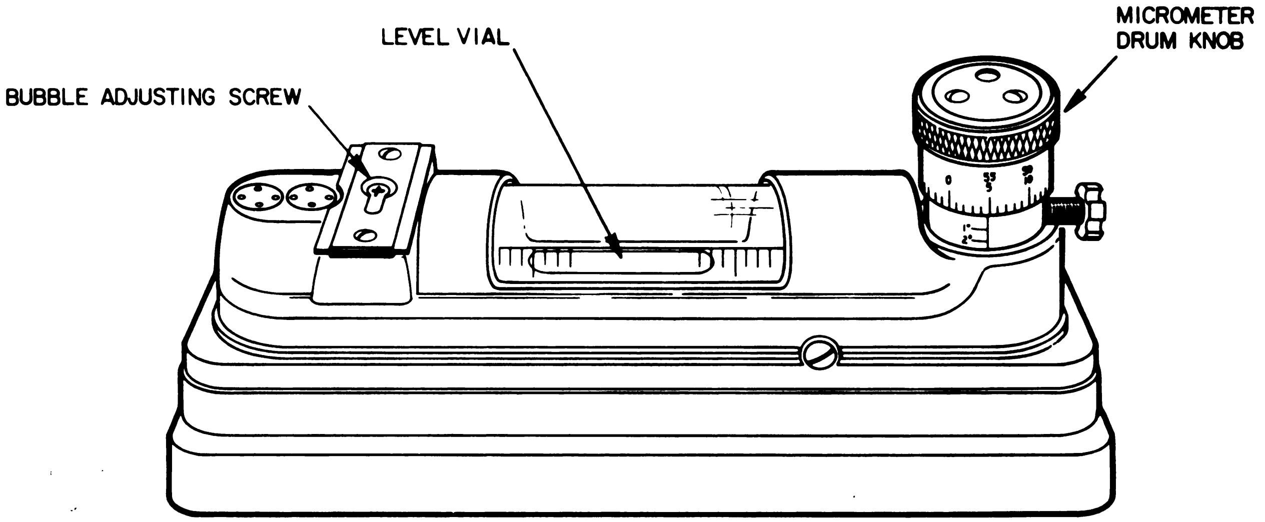

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Figure 7-12.—Hilger and Watts type TB4 level.

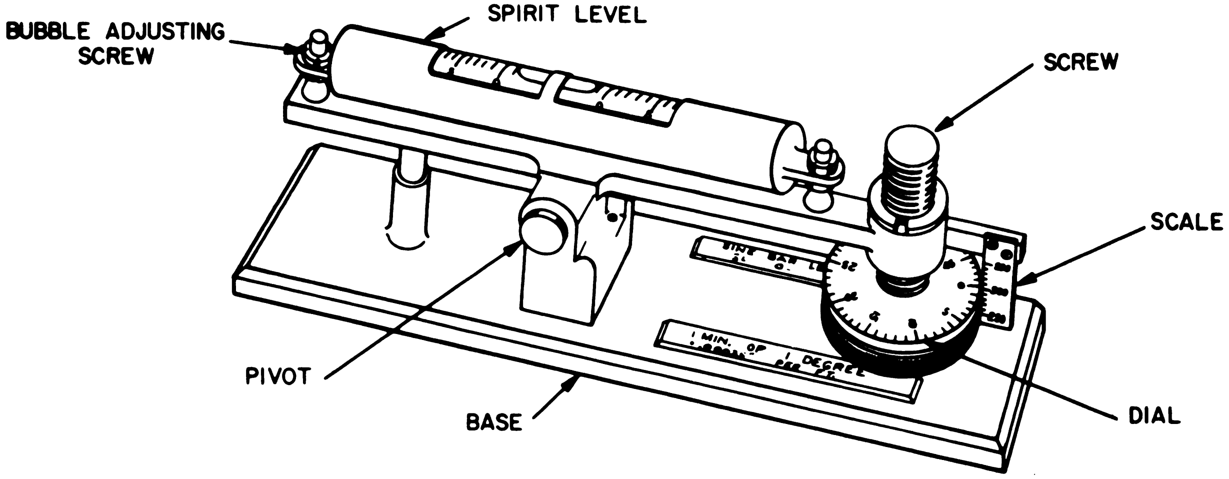

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Figure 7-13.—Sine bar type of level.

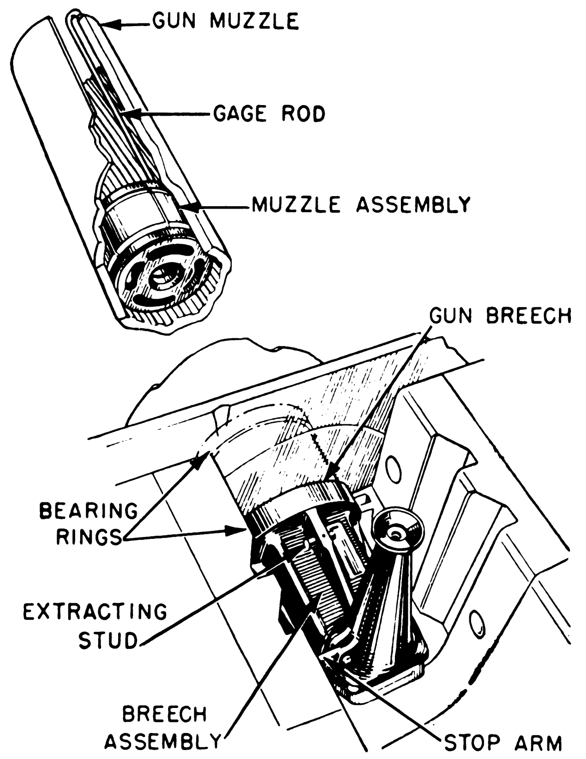

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Figure 7-14.—Typical boresight with self-contained optics.

be the bore axis of a gun, the centerline of a torpedo tube, the propagation axis of a radar beam, or some other similar line. Accurate alignment is not possible unless the pointing line is accurately determined.

Some alignment sights are temporarily installed. They are used for alignment and then removed from the equipment. Others are permanently installed and remain as part of the equipment.

### Boresight Telescope

One type of alignment sight is a *boresight telescope* which is used to represent the bore axis of a gun (fig. 7-14). These instruments are designed with self-contained optics in a single unit. The optics and features for positioning the instrument and securing it in the gun are all part of the unit. Most boresights of this class are provided with mounting surfaces that fit accurately into the gun bore. When the instrument is inserted in the gun bore, the LOS is brought into exact alignment with the gun bore axis.

## Self-contained Optics

In alignment using fixed, self-contained optics (fig. 7-15), the telescope is permanently mounted on a machined surface and accurately positioned so the telescope LOS is parallel to the pointing axis of the antenna dish. Actual alignment is accomplished by mechanical movement of the antenna dish so that the radar beam is parallel to the telescope LOS or movement of the telescope so that it is parallel to the radar beam.

## TRAM BAR AND TRAM BLOCKS

A *tram bar* is a device used to set an element to an exact position. It is used to determine the

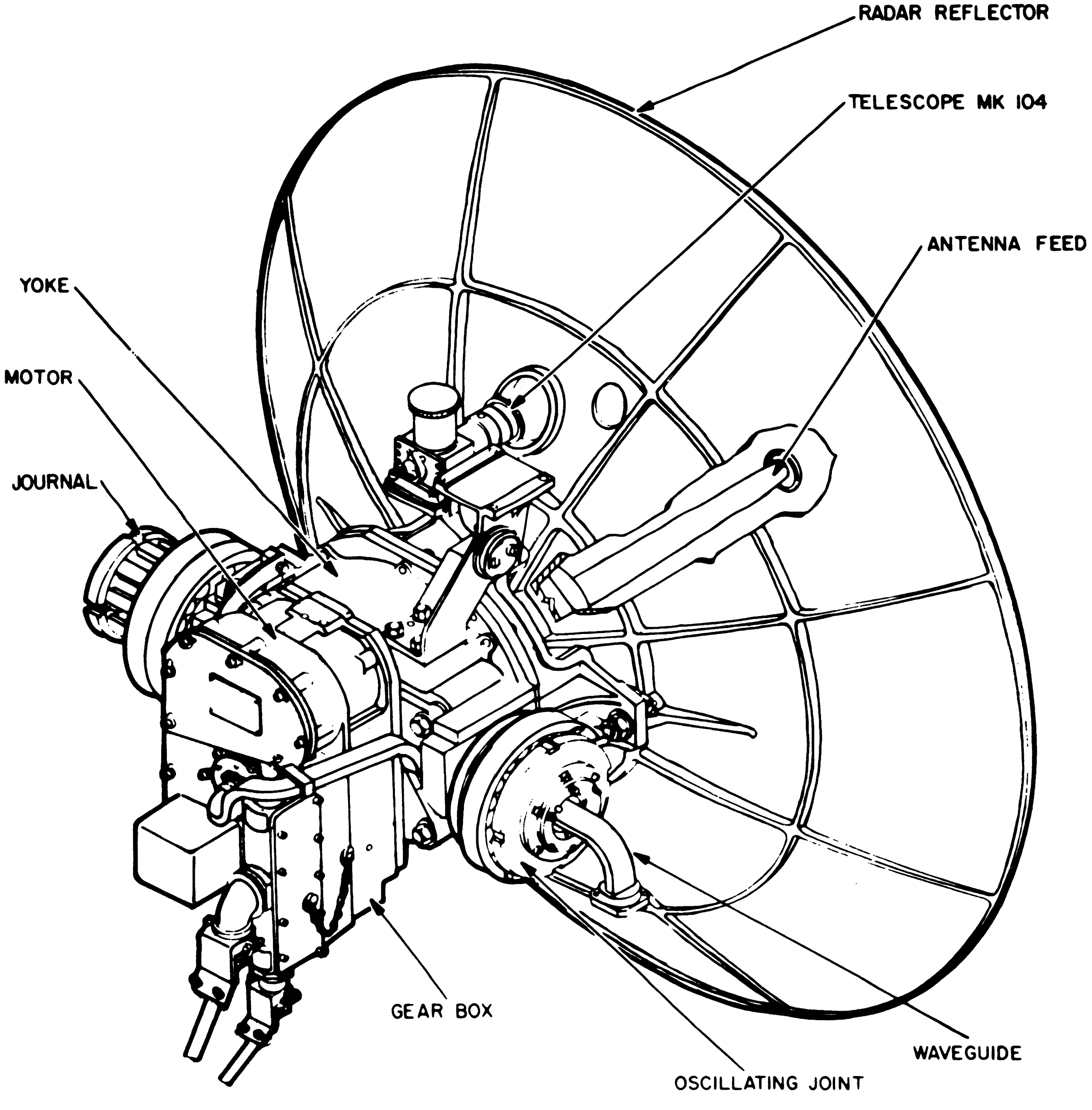

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Figure 7-15.—Typical fixed, self-contained alignment sights.

distance between two tram blocks that are fastened to the element. One block is fastened to the rotating structure of the element; one block is fastened to the fixed structure of the element (fig. 7-16). As shown, the tram bar is used to ensure the correct positioning of the movable block. Before continuing, let us closely examine the tram bar.

There are two types of tram bars—rigid and telescopic. The rigid tram bar is of fixed length and does not allow for error. The telescoping feature of the telescopic tram bar makes it more convenient and safer to use. For this reason, we will describe the telescopic tram bar. Both, however, accomplish the same purpose.

The telescoping tram bar (fig. 7-17, view A) consists of two parts, one bar sliding within another. The parts of the bars have a small amount of movement with respect to each other and are extended by an internal spring. A scribe mark on the inner part is visible through an opening in the outer part.

Engraved on the edges of the opening is a graduated scale that runs on each side of a zero mark. When the inner scribe mark and the outer zero mark are in line, the tram bar is at the correct length. As shown in figure 7-17, view B, a gage that is furnished with the instrument is used to check that the zero line and scribe mark match when the length is correct. Now that you have some concept as to what a tram bar is, consider once more the blocks.

The blocks (fig. 7-17, view C) are provided with pins that have cupped ends and fit the rounded ends of the bar. One block has a fixed pin, while the other has a movable pin. After the blocks are welded in place on the element, the movable pin can be adjusted so that the scribe mark and tram bar zero line match exactly when the dials of the element are at some known even reading. The movable pin is then tack-welded in place. To protect the ends of the pins from damage and corrosion when the pins are not in use, the pin ends are covered with grease-filled caps.

Tramming operations (fig. 7-16) should be performed with great care to prevent injury to personnel or damage to the equipment. The equipment power drives should not be used unless absolutely necessary. Position the equipment to the approximate tram position and insert the bar with the heavier end down. The bar should not

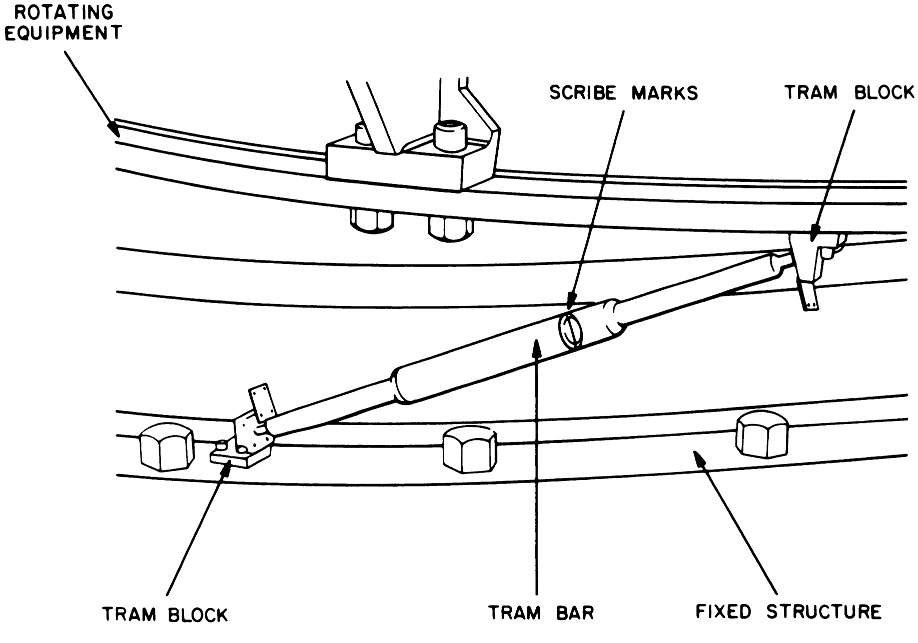

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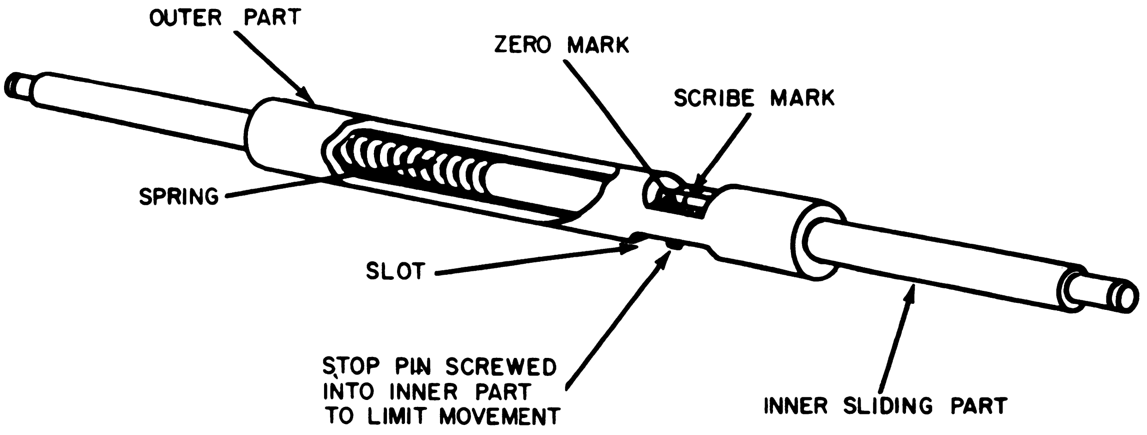
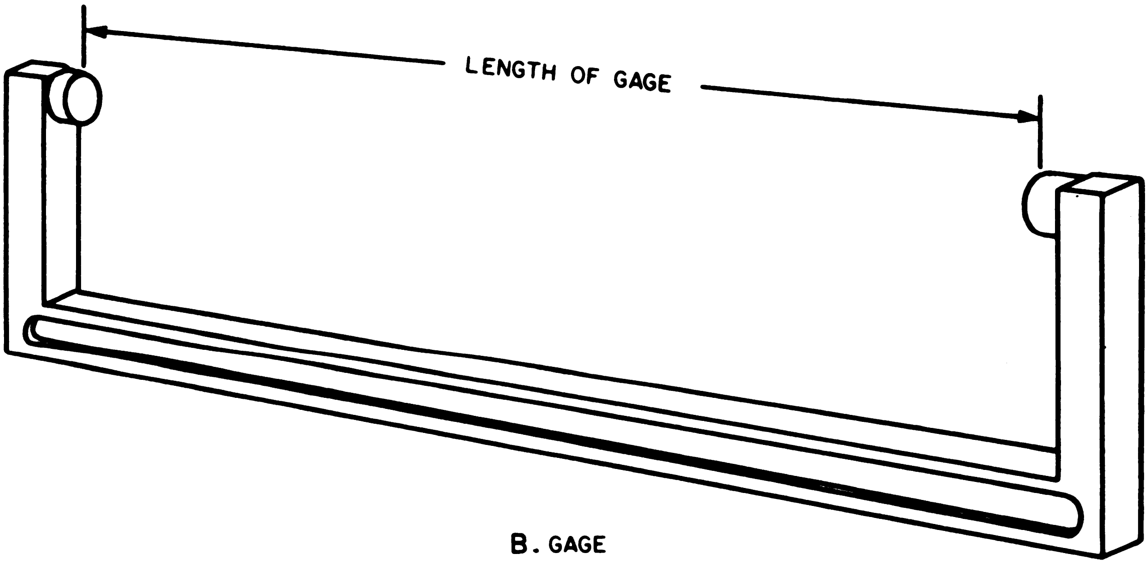
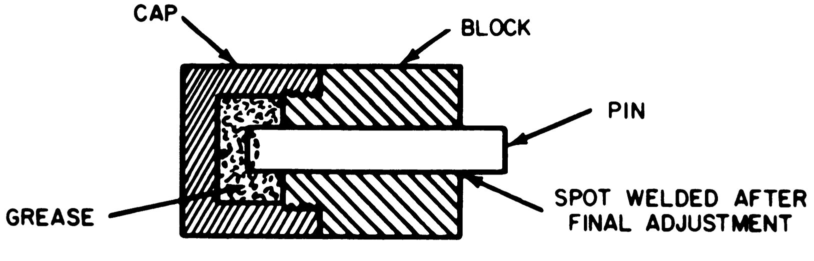
Figure 7-16.—Tram bar and tram blocks.



A. TELESCOPING TRAM BAR



B. GAGE



C. TRAM BLOCK AND PROTECTIVE COVER

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**Figure 7-17.—Telescoping tram bar and related equipment.**

be held in place while the tram blocks are moving with respect to each other; however, should this be necessary, the holding should be done only while the blocks are moving away from each other.

## BENCH MARKS

A bench mark (fig. 7-18) is a small metal plate containing an engraved cross. The plate is either brazed or welded to some rigid portion of the

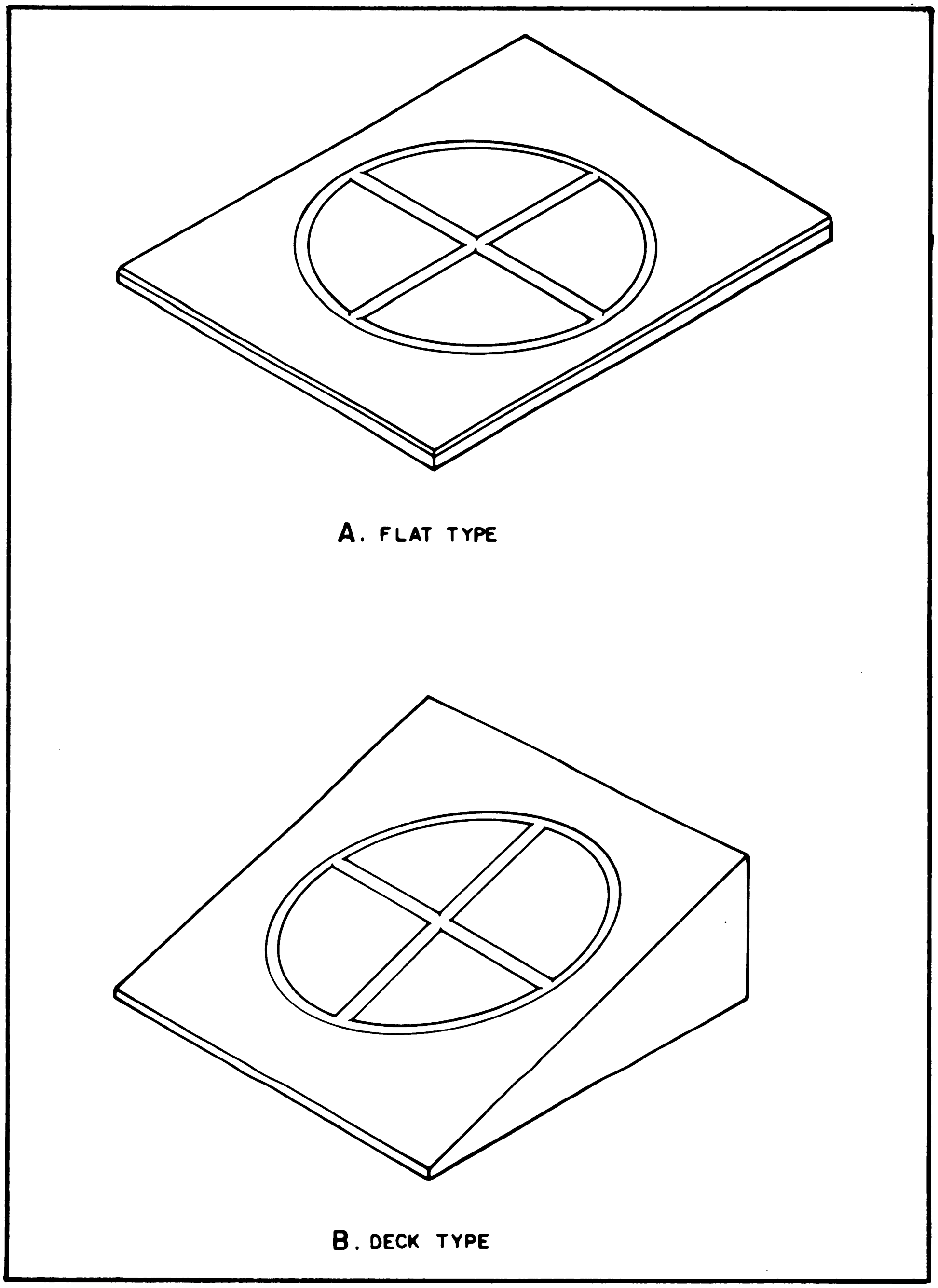

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Figure 7-18.—Typical bench marks.

ship's structure at a position where it can be sighted on with the reference element (director). The bench mark may be engraved on a flat plate for bulkhead mounting or on a block with an inclined surface so that the mark is clearly visible on the ship's deck.

A *bench mark* is a reference mark used in alignment to establish the angular relationships (elevation and train) of an element's line of sight to the ship's structure. When an element is sighted at its bench mark, its dial readings should agree with recorded values. If there is disagreement, alignment of the element is necessary.

### DIALS

Although the dials that must be read by alignment personnel are part of the equipment being aligned and cannot properly be considered to be equipment requiring alignment, a brief review is given of the precautions to be observed in reading dials.

The correct reading of dials is extremely important in alignment work. A simple mistake in reading a dial can cause great difficulty or unnecessary work. Such mistakes are often made, even by experienced personnel, and are made most often because of carelessness or undue haste. Before you attempt to read a dial, it is essential that you familiarize yourself with the values of the graduations and the manner in which the dials operate. This is particularly important if the dials are not read frequently. In such cases, several trial readings should be taken and checked with someone else before starting the alignment. Even familiar dials should be read systematically and deliberately.

Above all, no attempt should be made to hurry. A few extra seconds spent in making a careful reading may save hours of work involved in performing an unnecessary adjustment procedure.

## ALIGNMENT CONSIDERATIONS

There are certain major steps in combat system alignment that must proceed according to a specified sequence. Strict adherence to the order in which the steps are conducted is essential to the successful completion of the alignment task. The sequence in which these steps are to be performed is as follows:

1. Establishment of reference planes
2. Placement of reference marks
3. Establishment of parallelism
4. Performance of fire control radar rf-optical alignment
5. Establishment of train and elevation zero alignment
6. Performance of train and elevation space alignment (star checks)
7. Establishment of initial bench mark and tram reference readings.

Initially, these steps are accomplished by the installation activity during ship construction. Thereafter, shipboard alignment checks and verification consist mainly of bench mark checks, tram checks, and star checks. A brief discussion of each of these alignment considerations is presented in the following paragraphs.

### ESTABLISHMENT OF REFERENCE PLANES

The first major alignment step accomplished by a support activity is the establishment of reference planes. Referencing surfaces consist of the ship base plane (SBP), master reference plane (MRP), centerline reference plane (CRP), and weapons control reference plane (WCRP).

#### Ship Base Plane

The SBP is the basic horizontal plane of origin. The SBP is perpendicular to the ship's centerline plane and includes the base line of the ship, but it is not necessarily parallel to the keel of the ship. The SBP is used in establishing the MRP.

#### Master Reference Plane

The MRP is the first physical plane that is established for combat system alignment. The MRP is parallel to the SBP and is represented by a master level block or plate, usually located on one of the lower decks of the ship.

The plate is installed, aligned, and leveled only once after hull integration and is never adjusted thereafter. The master level plate serves as the reference for machining the foundations of the combat system equipment throughout the life of the ship.

### Centerline Reference Plane

The CRP is established during ship construction by the installation activity. It is the plane containing the ship's centerline and is perpendicular to the MRP. The CRP is the reference used to establish train zero alignment of all combat system equipment. The CRP is used throughout the life of the ship.

### Weapon Control Reference Plane

The WCRP is the plane to which the foundations and the roller path planes (RPP) of all combat system equipment are leveled. The WCRP is used throughout the life of the ship to determine RPP parallelism between the equipment of the combat system.

## PLACEMENT OF REFERENCE MARKS

The second major step is the placement of centerline marks, offset centerline marks, and equipment bench marks, which are performed by a shipyard or support activity.

### Centerline Marks

Centerline marks are established during initial construction to represent the ship's centerline. Small plates (at least three forward and three aft) are installed at intervals along the centerline to mark its location. Small plates are also installed in certain ship spaces to mark the location of the centerline.

### Offset Centerline Marks

Offset centerline marks are also established during initial construction to facilitate combat system alignment. The offset centerline is normally established parallel to or perpendicular to the ship's centerline. Offset centerline marks not parallel or perpendicular to the ship centerline are stamped or marked with the angles relative to the ship's centerline. Offset centerline marks are also established as required in interior compartments of the ship to facilitate the alignment of the combat system. The centerline and offset centerline marks are installed to preclude the necessity for repeating the centerline surveying during subsequent alignment.

### Bench Marks

Each equipment with an alignment telescope is provided with a bench mark, which can be sighted through the telescope. Equipment bench marks are installed at any convenient location that is visible through the equipment telescope. Equipment bench marks are used throughout the life of the ship to verify that the alignment is still within tolerance.

## ESTABLISHMENT OF PARALLELISM

The third major step is the establishment of parallelism between the RPPs of all equipment in the combat system. The degree of parallelism required is based on design and manufacturing criteria, the operational environment, and the requirements of the various operational modes. The steps necessary to achieve the degree of parallelism required are foundation machining, inclination verification, and interequipment leveling.

### Inclination Verification

Inclination verification consists of measurements of the tilt between two RPPs. The amount by which one RPP is tilted with respect to another RPP is expressed as the angle of inclination between the planes and the bearing where this inclination occurs. The tilt of the RPP is usually determined by the two-clinometer method or the horizon-check method.

### Foundation Machining

Foundation machining pertains to the physical processes required to attain a specified degree of parallelism and is performed by a support activity. Physical processes may involve using milling machines or welding premachined surfaces in place. Machining is accomplished with the ship afloat and loaded to simulate the full load deflection curve and the strains of major concentrated loads. The ship is kept in the specified loaded condition for a sufficient period of time (48 hours) before the start of machining operations to allow ship structural members to adjust to the load. Strict adherence to normal shipyard techniques of machining during periods of minimum temperature changes is observed.

### Interequipment Leveling

Equipment leveling is achieved by leveling rings, shims, adjusting screws, or software compensation. Leveling capabilities are used to achieve the RPI tolerances imposed by the minimum acceptable requirements or the various operational modes of the combat system. Where leveling capabilities are not provided, RPI tolerances are achieved through foundation machining. In some cases, where foundation machining was initially used to meet these tolerances, RPI compensation through computer software changes may be introduced if necessary.

## PERFORMANCE OF FIRE CONTROL RADAR RF-OPTICAL ALIGNMENT

The fourth major alignment step is the verification of fire control radar rf-optical alignment (collimation). During initial installation, the rf-optical alignment is established and the optics are secured in place. During subsequent alignment checks, the radar antenna or the optics, as applicable, are adjusted to correct any alignment error between the optical axis and the rf axis. When the radar is tracking, the rf axis is the reference used for target location. Rf-optical alignment is an equipment level test and is performed on a certified shore tower facility, or, in the case of some radars, it may be performed while tracking a target.

## ESTABLISHMENT OF TRAIN AND ELEVATION ZERO ALIGNMENT

Train and elevation zero alignment is the fifth major step in the sequence of alignment. This alignment, performed by the ship's force or a support activity, is conducted to ensure that all combat system equipment points to the same point in space when so directed.

There are two types of train and elevation zero alignment. For equipment with alignment or boresight telescopes, train zero is defined as the angle at which the telescope axis is parallel to the ship centerline plane; elevation zero is that angle at which the telescope axis is parallel to the RPP. Train and elevation zero alignment is carried out by physically positioning each equipment to train and elevation zero using surveying techniques and zeroing the dials and synchros, or by compensating for the train and elevation errors through computer software changes. For equipment not having telescopes, train and elevation zero alignment is accomplished by matching an indicator to a scribe mark or plate and zeroing the dials and synchros.

## PERFORMANCE OF TRAIN AND ELEVATION SPACE ALIGNMENT (STAR CHECKS)

The sixth major step of initial alignment is train and elevation alignment between the alignment reference and other combat system equipment. This is accomplished by comparing equipment position when the optical axes are made parallel by sighting on a celestial body. If the train and elevation readouts for the equipment do not agree within the operational tolerances previously established for that equipment, alignment is necessary. After corrective alignment is accomplished, a new set of tram or bench mark readings must be taken and recorded. This alignment check can be performed by ship force or support activities.

## ESTABLISHMENT OF BENCH MARK AND TRAM REFERENCE READINGS

The last major step in the alignment sequence is the establishment of reference readings that are performed by a support activity or by ship's force. Reference readings are established to furnish an easy means of checking train and elevation alignment in the future. This is necessary because the dials or synchros may become misaligned as a result of vibration and normal wear or equipment disassembly for the replacement of worn parts.

Tram and bench marks are provided to facilitate checking combat system equipment at a definite train and elevation position. The position selected may be any convenient value within the limits of the equipment movement. The dial readings for these positions are recorded on the sheets provided in the alignment smooth log. If the equipment remains aligned correctly for zero train and elevation, the recorded dial readings are the same whenever the equipment is moved to the tram or bench mark position.

The alignment verification obtained by using a bench mark is accurate only if the angle between the reference line and the position of the pointing line established by the bench mark does not change as a result of hull distortion or some other cause. Adjustments to equipment should not be made using the result of a single bench mark check. Instead, bench mark results should be recorded each time they are performed so that it can be determined when a bench mark error begins repeating itself and becomes an indication that further alignment checks are required.

A tram bar and tram blocks, discussed earlier, may also be used to establish an angle by determining a definite distance between a point on the rotating structure of the equipment and a point on its fixed structure. An error, as defined by tram readings, may also result if the fixed structure shifts on its mounting. Adjustments to equipment, like bench marks, should not be made on the basis of a single tram check.

Some equipment have both bench marks and trams. When the bench mark reading has changed and the tram reading remains unchanged, the extent of hull distortion is revealed.

## ALIGNMENT PROCEDURES

Alignment is considered to be corrective maintenance and should be conducted only when test results indicate that an alignment problem exists. Specific fault isolation procedures for your weapons system are contained in the applicable *Combat System Alignment Manual*, SW225-XX-CSA-010.

The following procedures are of a general nature and do not address the specific alignment procedures of any specific equipment. Furthermore, these procedures do not require outside services, the use of special tools, or equipment not normally carried aboard ship.

### BENCH MARK CHECKS

Before doing bench mark checks, operators using equipment with cross-level or traverse movement should ensure these movements are locked at zero. Parallax correctors should be set to zero, and if any adjustments are needed to any equipment, a careful review of the adjustment procedure in the appropriate equipment publication should be checked.

The equipment is trained and elevated until the LOS is on the bench mark. If the equipment has more than one telescope, the one specified as the reference telescope for the alignment should be used.

The equipment is moved in train (elevation) away from the position established in the preceding paragraph, and then it is carefully positioned until the telescope is again sighted on the bench mark. The equipment should always be positioned to the bench mark in the same direction so that any lost motion in the gearing is taken up. The train (elevation) dials are read, and the readings are recorded.

The above procedures are repeated until five sets of data have been recorded for each direction of train and elevation. The dial readings for train are added and the total is divided by the number of readings taken to obtain the mean train reading. Elevation is computed the same as train. Obtaining the readings in this manner splits any lost motion.

The mean readings obtained in the above steps are compared to the recorded bench mark reading. If there is a significant difference, this difference is considered in the light of results from previous checks, and it should be decided whether an adjustment is necessary. No adjustment should be made until other alignment checks have been conducted to ensure that an actual alignment error is present.

### TRAM CHECKS

Before doing any tram checks, operators at equipment with cross-level or traverse movement should ensure these movements are locked at zero. If the equipment is provided with a parallax corrector, the parallax correction must be set to zero.

The equipment is trained or elevated as applicable until the tram bar fits between the tram blocks. The equipment is then carefully positioned until the tram bar scribe marks are aligned, then held motionless until the tram position is recorded. The equipment is then positioned so that the tram blocks are moved closer to each other. Equipment movement is then reversed and carefully positioned until the tram bar scribe marks are again aligned. The tram position is again recorded.

The above procedures are repeated until five sets of data have been recorded for each direction of equipment movement. The equipment position readings for train are added and the total is divided by the number of readings taken to obtain mean train reading. The mean elevation reading is computed the same as train. Obtaining the mean readings in this manner splits any lost motion.

The mean readings obtained in the above steps is compared with the recorded tram reading. If there is a significant difference, further alignment checks should be performed before making any adjustments.

## RPP INCLINATION VERIFICATION

The best method for obtaining roller path data is by using the two-clinometer method. However, the two-clinometer method can be used only when the ship is tied up at a dock or anchored in calm water. An alternate method is the horizon-check method, which can be performed underway as long as the water is calm with little rolling or pitching motion. Horizon checks are performed as follows:

1. Communication is established between the reference equipment and the equipment to be checked. The following parameters are set to zero: cross-level and traverse, sight angle and sight deflection, and the output from elevation parallax equipment.
2. The reference equipment and the equipment to be checked are trained to the same bearing. The reference equipment is positioned in elevation so that its pointing line swings up and down across the horizon as the ship rolls and pitches.
3. The other equipment is positioned in elevation so that its pointing line crosses the horizon at the same instant as that of the reference equipment. At the instant the operator of the reference equipment sees the horizontal cross hair cross the horizon, he/she calls MARK to the operator of the other equipment. The operator of this equipment notes whether the horizontal cross hair is above or below the horizon at this instant. The operator then adjusts the equipment to remove the error so that the horizontal cross hair is on the horizon at the instant the reference equipment operator calls MARK. The operator then calls SET to the reference equipment operator to inform him that he is on target. When marking on the horizon, each operator should always elevate the equipment in the same direction so that lost motion is taken up.
4. The elevation dials of each equipment are read and the readings are recorded.
5. The procedures outlined in steps 1 through 4 are repeated, but the horizon is approached in the opposite elevation direction so that lost motion is taken up in the opposite direction. The elevation dials of each equipment are read and the readings are recorded.
6. The corresponding readings taken in steps 4 and 5 are added and the totals are divided by two to obtain the mean reading for each equipment. These mean readings split any lost motion.
7. The procedures described in steps 2 through 6 are repeated every 30° as the equipment is trained through 360°. Analysis of the data resulting from horizon checks is discussed later in this chapter.

A factor that causes differences between dial readings is the heights of the equipment. This elevation difference, known as the dip difference angle, is shown in figure 7-19. The dip angle is similar to elevation parallax; it depends only on the heights of the equipment above the waterline and is not affected by train. As long as roll and pitch angles are not large, the heights of the equipment above the waterline do not change significantly. The dip difference angle remains constant during the horizon check, and its magnitude can be determined if the heights of the equipment above the waterline are known.

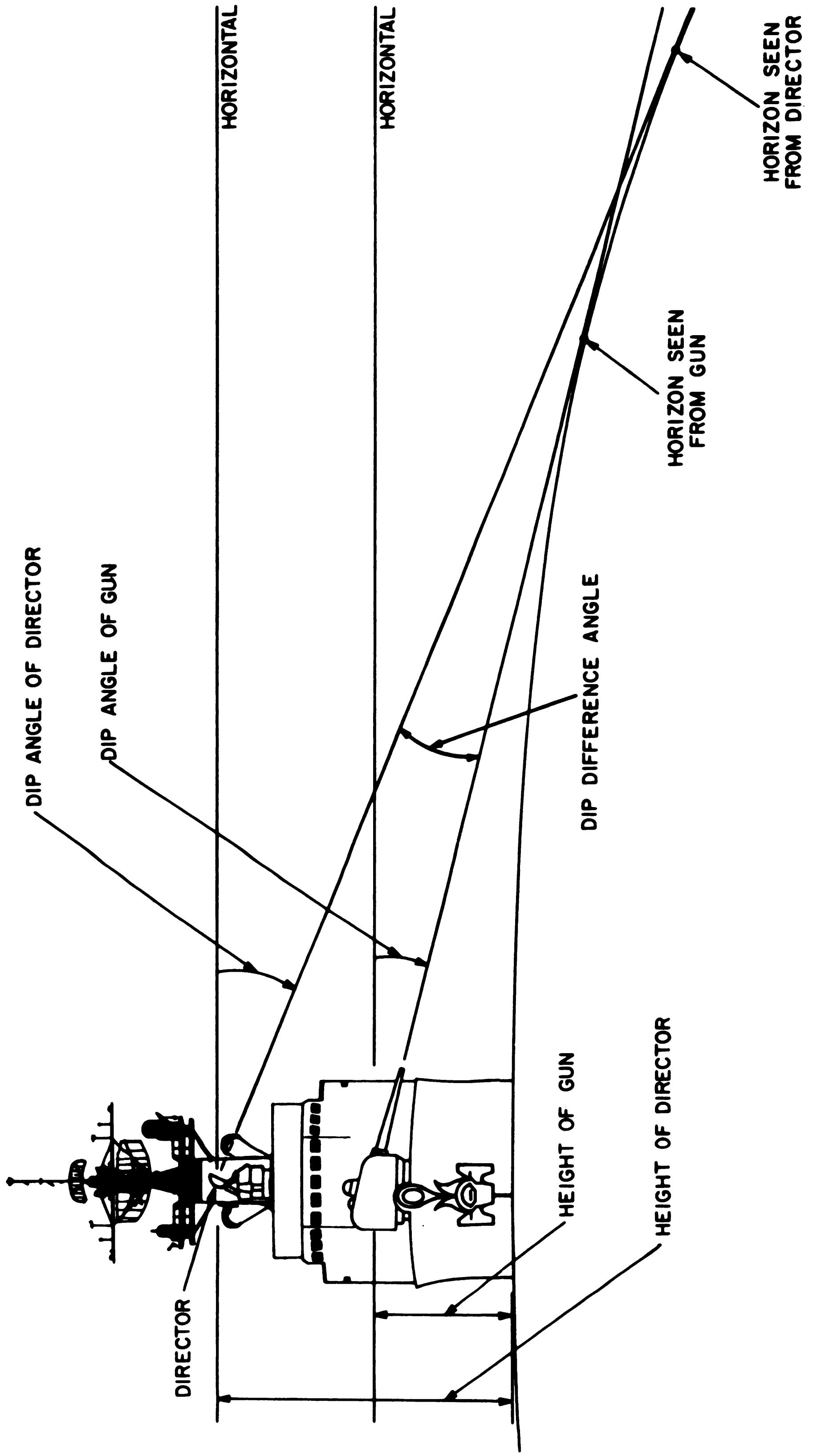

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Figure 7-19.—Dip angle and dip difference.

Dial reading differences are also caused by misalignment of dials between equipment being aligned and the reference equipment. This difference is not affected by train, roll, or pitch.

A further difference in dial readings results from the roller paths not being aligned between equipment. Unlike differences caused by dip or dial misalignment, roller path misalignments are variable with the train angle. This variation is in the form of a cosine function of the train angle. Each dial reading difference recorded in a horizon check is the sum of two constant values and a varying value.

After the varying portion of the horizon-check data has been analyzed to determine the values necessary for the roller path alignment, the constant portion of the data is analyzed to determine the extent of any dial misalignment.

Once the dip difference angle for an equipment is found, the dial misalignment is found by subtracting the dip difference angle from the total constant factor in the horizon-check data. If the result is positive, indicating that the dial reading is too high, the dials are adjusted to reduce the reading. If the result is negative, indicating that the dial reading is too low, the dials are adjusted to increase the reading. After the dials are adjusted, the elevation synchros must be checked to ensure that they are at electrical zero when the dials read zero.

## ESTABLISHMENT OF TRAIN ZERO

A transit (theodolite) is set up over a centerline reference mark or an offset centerline reference mark where it can conveniently sight the equipment to be aligned. A clinometer is mounted on the equipment to be aligned. The transit is leveled to the equipment roller path using the level vial on the transit and the clinometer mounted on the equipment.

Transit leveling is accomplished by taking the clinometer and transit inclination readings simultaneously at 0°, 90°, 180°, and 270°. Leveling corrections are determined by computing the differences between the clinometer and transit inclination readings at each bearing and comparing these differences. Correction is made by adjusting the transit base screws.

Next, the transit is referenced to the ship's centerline by sighting it on a second centerline reference mark. Verify the placement of the transit by plunging it to sight a third centerline reference mark. If the transit is set up over an offset centerline reference, the transit should be verified the same as when using the centerline reference marks.

With the transit set up and leveled, the equipment and transit are trained and elevated until the equipment telescope and transit can sight the illuminated reticle of each other, as shown in figure 7-20, view A. To aid in sighting from the equipment to the transit, the transit may be illuminated with a flashlight held at the eyepiece. The process is reversed when sighting from the transit. This process is repeated until the telescopes are aligned with each other. To eliminate lost motion, sightings must be taken in both directions.

With the transit telescope and equipment pointing line aligned to each other, the transit is read to obtain angle b between the pointing line and the offset centerline. This angle is recorded.

The equipment is aligned in train by setting the train dials as determined by the transit angle. As shown in figure 7-20, view B, the equipment is trained until the dials read zero; the synchros are now adjusted for electrical zero. If an equipment cannot be trained to 0°, it is trained to 180° and the synchros are set 180° from 0°.

In *elevation zero*, a transit is set up and aligned to the equipment as described for train zero procedures; except now, the elevation angle of the transit is read. This angle is equal to the depression of the equipment with respect to its own RPP. The equipment parallax correctors and RPI compensators must be set to zero before conducting this alignment.

Next, the elevation dials are adjusted to read the depression angle. Then the equipment is

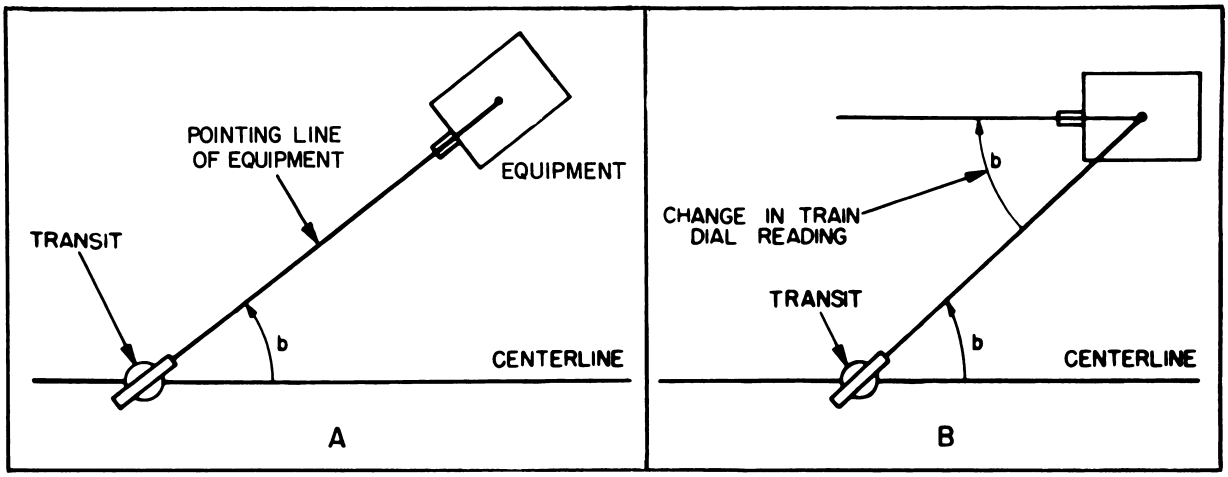

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Figure 7-20.—Measuring angle between pointing line and centerline.

elevated until the dials read exactly zero, and the elevation synchros are set to electrical zero. The RPI compensation values and the parallax values are now entered, and the elevation zero point becomes parallel to the RPP of the WCRP.

## STAR CHECKS

Star checks are used to ensure that all equipment of the combat system point to the same point in space when so directed. The following paragraphs describe the basic procedures for conducting star checks.

It is preferable to conduct star checks when moored alongside a pier to minimize the effects of ship motion. Star checks can be conducted while the ship is at anchor; it is necessary, however, to allow the wind and current to stabilize the ship. It is desirable to select a star at less than 30° elevation for use as a target.

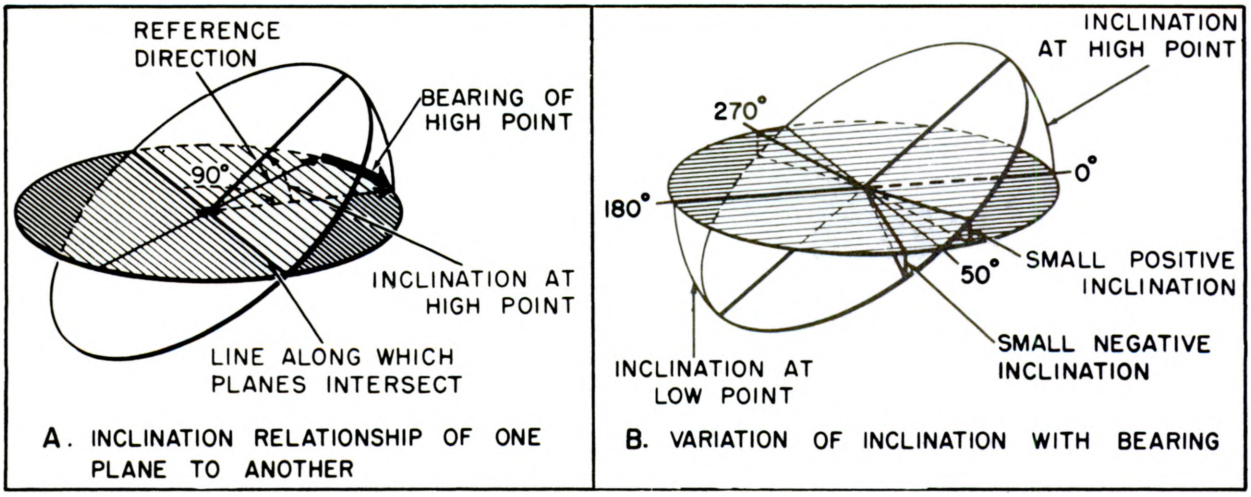
The operator at the alignment reference coaches the other operators to ensure that they approach the target from the same direction. When all stations are on the target simultaneously, the equipment position is recorded.

It is imperative that all equipment approach the target from the same direction. When any equipment overshoots the target, it must be repositioned and made to approach the target from the original direction. This procedure eliminates the effects of lost motion.

The procedures outlined above are repeated until at least five sets of data have been recorded by approaching the target from each direction of train and elevation. A second target, which is approximately 180° in bearing from the first target, is selected and a complete set of data is taken using the second target.

## ROLLER PATH INCLINATION ANALYSIS

Because of variations in the degree of accuracy achieved in foundation marking, an inclination difference exists between the reference plane and the roller path plane (RPP) of each equipment. The inclination difference between two planes can be determined by plotting and analyzing the data obtained by using the clinometer or horizon-check method. The following discussion assumes data is taken using the horizon-check method.


REFERENCE DIRECTION
BEARING OF HIGH POINT
90°
INCLINATION AT HIGH POINT
LINE ALONG WHICH PLANES INTERSECT
A. INCLINATION RELATIONSHIP OF ONE PLANE TO ANOTHER
INCLINATION AT HIGH POINT
270°
0°
180°
50°
SMALL POSITIVE INCLINATION
SMALL NEGATIVE INCLINATION
INCLINATION AT LOW POINT
B. VARIATION OF INCLINATION WITH BEARING

55.368

Figure 7-21.—Different tilt relationships.

### Bearing of The High Point

Figure 7-21, view A, shows the relationship between two planes. The tilt inclination is expressed by giving the greatest angle of inclination between the planes and the bearing at which it occurs. This position is normally referred to as bearing of the high point ($B_{HP}$) and is always 90° from the line created by the intersection of the two planes.

Changes in the bearing show different inclination angles between the planes, as shown in figure 7-21, view B. At successive bearings measured clockwise from the high point, the inclination remains positive, but it decreases in magnitude until it is zero at 90° from the high point where the planes intersect. In the next 90°, the inclinations are negative and gradually increase in magnitude until the maximum negative inclination or low point occurs 180° from the high point.

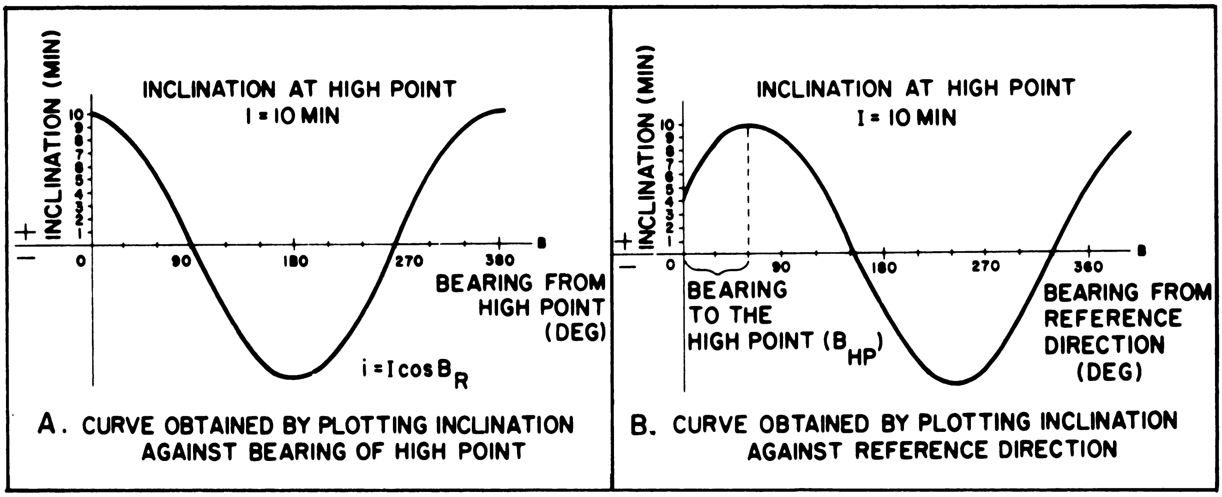
As the bearing angle is increased, the inclination angle remains negative, but it decreases in magnitude to zero 270°, and then becomes positive and increases in magnitude until it again reaches the maximum positive value at 360°.

Using trigonometry and geometry, a formula can be derived to express the inclination of one plane in respect to another. This formula is given as follows: $i = I \cos B$, where $\underline{I}$ is the inclination between the planes at the high point; $\underline{i}$ is the inclination angle at any bearing from the high point.

Figure 7-22, view A, shows the curve obtained when these inclinations are plotted in rectangular coordinates from the high point of the inclination. Figure 7-22, view B, shows the same inclination plotted in rectangular coordinates from the reference direction of the equipment. RPI data is normally obtained in this manner.

### Plotting RPP Data Using Rectangle-Coordinate Method

Since the high point can occur at any angle and roller path readings are taken at a limited number of train angles, it is unlikely any readings will be at exactly the high point. For this reason, the inclination difference data taken from horizon checks are plotted on a graph, as shown in figure 7-23, view A. The points on the graph are faired by drawing a smooth curve through them, as shown in figure 7-23, view B. The curve has the form of a cosine curve, but it is displaced above the horizontal axis of the graph. This displacement is proportional to the difference in height above

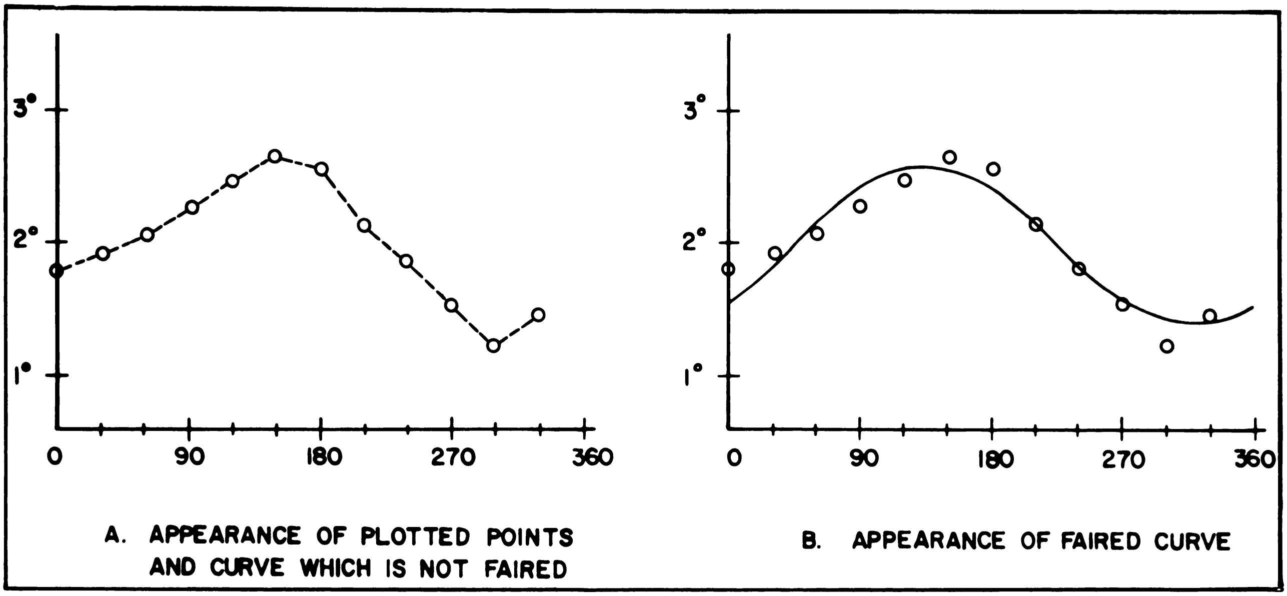


55.369

Figure 7-22.—Inclination plots.

the waterline of the reference line of sight (LOS) and the equipment LOS (dip difference), plus any elevation dial error. Therefore, when plotting horizon check data, the amount of dip difference between the alignment reference and the equipment being checked must be known and plotted on the graph. To obtain the dip angle for equipment, use the formula $d = 0.98\sqrt{h}$, where h is the height of the equipment above the waterline.

In the horizon-check method, the cosine curve is the result of reading dial settings when the LOS is on the horizon. As the equipment is trained toward the low point, the LOS falls below the



55.370

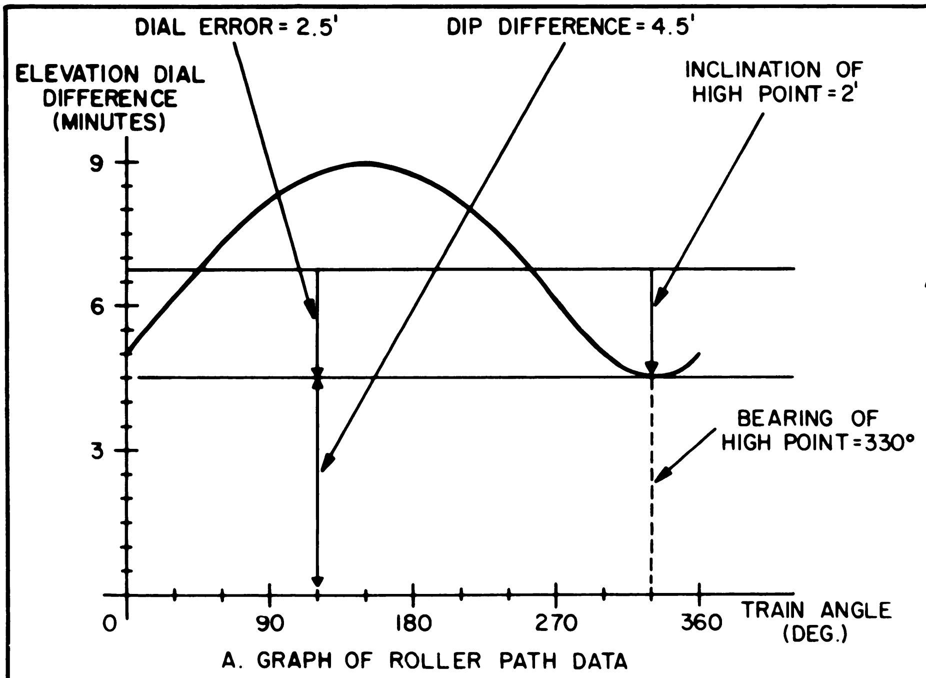
Figure 7-23.—Plotted points and curve faired through the points.

horizon requiring the equipment to be elevated to return the LOS to the horizon. This action causes an increase in the dial reading as a result of a decrease in RPI. Because of this inversion of motion, the $B_{HP}$ plotted from horizon check data on the cosine curve is actually the low point of that curve. An example of this action is shown in figure 7-24.

### 180° Polar-Coordinate Method

Another method of plotting roller path data is the 180° polar-coordinate method. When data are plotted by the 180° polar-coordinate method, the curve resulting from the variation of the RPI takes the form of the diameter of the circle, which is equal to twice the inclination of the roller path. This circle, which can be faired by using a compass, can then be used to determine the inclination at the high point and the $B_{HP}$. When the 180° method is used, the data are plotted on polar-coordinate paper, as shown in figure 7-25, and the actual procedure for analyzing roller path data by the 180° polar-coordinate method is as follows:

1. If possible, obtain a form like that shown in figure 7-25 and list the data in columns 1 and 2.
2. In column 3, add 180° to each bearing in column 1.
3. In column 4, list the dial difference reading corresponding to each bearing in column 3. (Columns 3 and 4 show the same data as columns 1 and 2, but the entries are shifted by 180°.)
4. Subtract the readings in column 4 from the readings in column 2, and enter the differences in column 5. If a reading in column 4 is greater than the related reading in column 2, the result will be negative. In such cases, be sure to include the minus sign.
5. Plot the values in column 5 against the bearings in column 1. Be sure to plot negative values opposite to the direction of the related bearing angle. The plotted points should progress approximately in a circle for the first 180° and then progress over the same circle in the next 180°. The points plotted in the second 180° should be superimposed



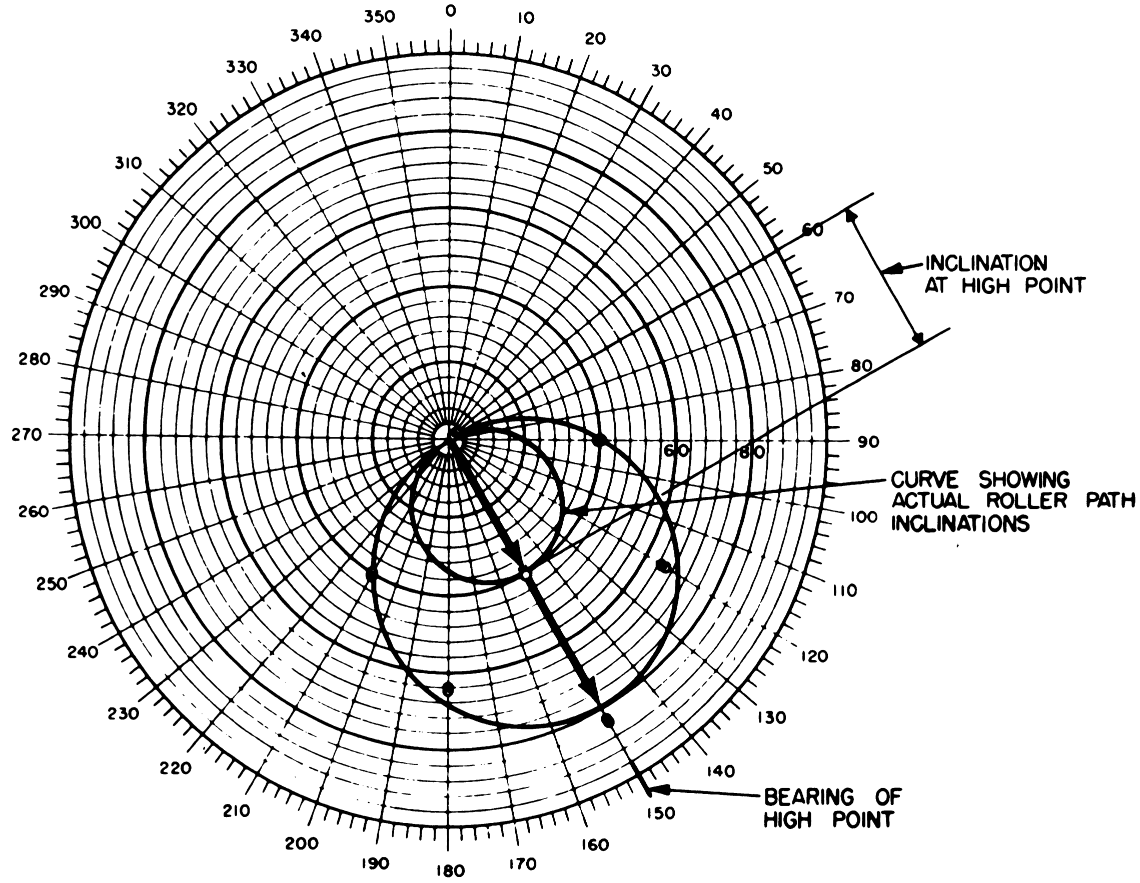
A. GRAPH OF ROLLER PATH DATA

| TRAIN ANGLE DEG. | ELEVATION DIAL DIFFERENCE (MINUTES) |
|---|---|
| 0 | 5.0 |
| 30 | 6.0 |
| 60 | 7.0 |
| 90 | 8.0 |
| 120 | 8.5 |
| 150 | 9.0 |
| 180 | 8.5 |
| 210 | 8.0 |
| 240 | 7.0 |
| 270 | 6.0 |
| 300 | 5.0 |
| 330 | 4.5 |
| 360 (0) | 4.0 |

B. TABULATED ROLLER PATH DATA

55.371

Figure 7-24.—Curve produced by plotting horizon check data.



| 1<br>TRAIN ANGLE (DEG) | 2<br>DIAL DIFFERENCE READING | 3<br>TRAIN ANGLE (DEG) | 4<br>DIAL DIFFERENCE READING | 5<br>DIFFERENCES (COL.2 (−) COL.4) (MIN) |
|---|---|---|---|---|
| 0 | 1°47' | 180 | 2°51' | -64 |
| 30 | 1°59' | 210 | 2°39' | -40 |
| 60 | 2°20' | 240 | 2°19' | 01 |
| 90 | 2°40' | 270 | 2°00' | 40 |
| 120 | 2°52' | 300 | 1°46' | 66 |
| 150 | 3°01' | 330 | 1°37' | 84 |
| 180 | 2°51' | 360 | 1°47' | 64 |
| 210 | 2°39' | 30 | 1°59' | 40 |
| 240 | 2°19' | 60 | 2°20' | -01 |
| 270 | 2°00' | 90 | 2°40' | -40 |
| 300 | 1°46' | 120 | 2°52' | -65 |
| 330 | 1°37' | 150 | 3°01' | -84 |
| 360 | 1°47' | 180 | 2°51' | -64 |

55.372

Figure 7-25.—Analyzing data using 180° polar-coordinate method.

on, or very close to, the points plotted in the first 180°.

6. Fair a circle through the points using a compass. Change the setting of the compass and move the needle on the graph until the circle is found that best fits all of the points. The circumference should pass exactly through the pole. After drawing the circle, mark its center.

7. The high point of the curve lies on the diameter through the pole of the graph. Draw this diameter by drawing a line through the pole and through the center of the circle.

8. The diameter drawn in step 7 is at the same bearing as the high point of the RPP, but its length represents an inclination that is twice that of the inclination at the high point of the RPP. Therefore, determine the bearing of the roller path high point by noting the $B_{HP}$ of the curve. Determine the inclination at the high point by taking one-half the inclination at the high point of the curve.

## ROLLER PATH INCLINATION CORRECTION METHODS

In a combat system, it is desirable to have all equipment RPPs parallel to each other. This condition does not exist, and if it did, normal conditions aboard a ship would cause the RPPs to change as a result of hull and superstructure distortion.

Foundations on which equipment is set are machined so that when the equipment is installed, the RPPs are parallel within prescribed limits. The closeness of the limits depends on whether the roller path of the equipment can be modified after installation.

After installation, light equipment can be modified by using shims, leveling screws, and leveling rings. In heavier equipment, RPIs may be compensated for by means of a mechanical or electrical roller path tilt corrector. An additional method of RPI compensation is to correct the position orders for the inclination differences between the receiving equipment and the alignment reference using computer software.

### Mechanical Roller Path Tilt Corrector

Mechanical roller path tilt correctors do not correct for all errors caused by roller path tilt. Mechanical tilt correctors compensate for pointing line elevation errors into which the roller path tilt enters directly, but they do not correct train errors that also result from roller path tilt. Because these errors are usually small and because a device for correcting them would be considerably more complicated than that for correcting elevation, the train errors are not considered.

A mechanical roller path tilt corrector continuously computes the inclination angle of an RPP with respect to the reference plane. The roller path tilt corrector then combines the computed correction angle with the transmitted elevation angle from the controlling equipment.

### Electrical Roller Path Tilt Corrector

Electrical roller path tilt correctors are analog devices that solve the basic roller path problem and produce output signals that are proportional to the inclination of the high point at any given angle. Electrical roller path tilt correctors operate similar to mechanical roller path tilt correctors, except the output is an electrical signal that is summed with equipment elevation position orders.

In some cases it is desirable to correct both train and elevation errors that result from roller path tilt. In these cases a special, electrical roller path tilt corrector outputs electrical signals that are summed with equipment train and elevation position orders.

### Computer Software

Digital computer programs can be written so that elevation, or train and elevation errors that arise because of RPI, can be calculated and applied as correction factors to transmitted position quantities.

The software compensates in a manner similar to that of the electronic compensator. The inclination and $B_{HP}$ are placed in the adaptation data of the computer memory, and the digital program performs the required mathematical operations to modify the inclination as a result of bearing from the high point. The resultant computations are then used to modify the positional orders output by the computer. When it is necessary to modify the tilt correction of a software program, the cognizant agency should be notified and a new program written incorporating the correct values of inclination and $B_{HP}$.

### Modifying a Tilt Corrector Setting

When roller path data is taken afloat, the measurements are made with some setting already in the roller path tilt correctors. If the data indicates a relative RPI for equipment under these conditions, the setting of the roller path tilt corrector must be modified.

For equipment having the correctors that actively affect the elevation dial reading in all modes of operation, it is necessary to geometrically add any existing inclination at the bearing set on the tilt corrector to the new values of inclination and bearing that are deemed necessary. This is usually the case when the output of a mechanical tilt corrector is algebraically added to the response position of an equipment.

This geometric (vector) addition is not required when the output of a tilt corrector is used to modify equipment position orders from a remote source, as would be the case when the tilt correction is an integral part of a digital computer software program.

For applicable equipment, the manner in which a roller path tilt corrector setting must be modified when the roller path data show that the setting is not correct can be determined on a vector diagram, as shown in figure 7-26. (Bearing and error readings in figure 7-26 are used for illustration purposes only.) To determine the final compensation setting, the following steps are performed:

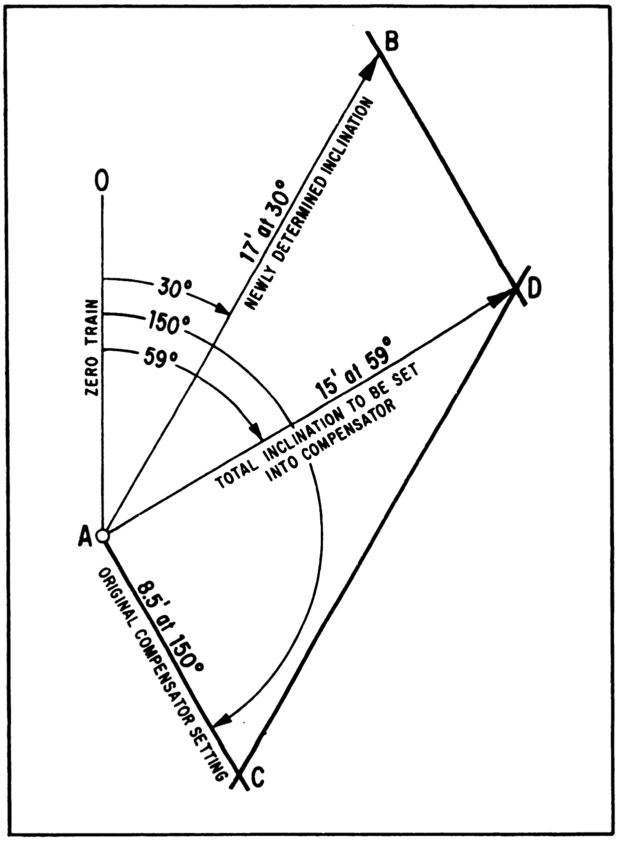
1. The line OA is drawn to represent zero train.

2. The original setting of the compensator (8.5 ′ at 150 °) is plotted as line AC. This is done by measuring off the angle clockwise from OA and measuring the inclination on that line to a convenient scale.

3. The inclination found (17 ′) is plotted as AB on a bearing of 30 °.

4. CD is drawn parallel to AB, and BD is drawn parallel to AC. These lines intersect at D.

5. Line AD is drawn from the origin to D. This line represents the total inclination. Its bearing (59 °) and length (15 ′) may be read according to the previously established scale. This is the data that must be set into the compensator.


B
O
17' at 30°
NEWLY DETERMINED INCLINATION
D
ZERO TRAIN
30°
150°
59°
15' at 59°
TOTAL INCLINATION TO BE SET INTO COMPENSATOR
A
ORIGINAL COMPENSATOR SETTING
8.5' at 150°
C

110.86

Figure 7-26.—Compensator-setting calculation.

It should be noted that compensators are constructed to read the error rather than the correction. Thus, if the error is 15 ′ at 59 °, the bearing scale is turned to 59 °. Then, the inclination of 15 ′ is set on the inclination scale, and the adjustment is completed.

## WEAPONS SYSTEMS SMOOTH RECORD

This record title is akin to what was formerly known as the battery smooth log and the fire control smooth log, among others. Thus, the weapons systems smooth record is the title that may be applied to all smooth logs that are required to be kept.

Most often the weapons systems log contains sections devoted to the following items:

Alignment—Summaries of alignment data for each GFCS and MFCS, train checks, bench marks established and recorded, roller path compensator settings, horizon checks, radar antenna alignment record, and so forth.

Erosion—Star gage data, erosion gage data, equivalent service rounds (ESR), pseudo equivalent service rounds (PESR), and a record of bore searchings.

Rounds fired—Entries in tabular form for each gun barrel by serial number which show rounds fired, type of projectiles, powder charge, powder index, and ESR (equivalent service rounds).

Rangefinder—Record of rf calibration checks and adjustments and a smooth copy of each operator's **B** curves.

Radar—Dates and results of radar adjustment, collimation, calibration, and double-echo checks. Any corrective measures taken, such as the negative range zero set from the results of the double-echo check.

Exercises and rounds fired—Date and type of exercises or action firing. Overall results, plus a complete summary for unsatisfactory firings and corrective measures taken. List the ACTH (arbitary correction to hit) or any other initial spot that was used.

Alignment data must be documented upon completion to provide information for future checks and to inform responsible personnel of equipment and subsystem alignment status. A complete and accurate alignment data package is essential for effective combat system alignment.

## SUMMARY

This chapter has presented the basic procedures involved in weapons system alignment. You have seen that alignment is based on certain elementary geometric concepts, including the concepts of parallel lines, parallel planes, pointing line, and reference frame. Alignment, then, is essentially the establishment of a reference plane, pointing line, and so forth, and then adjusting the elements of a weapons system so that the roller path plane and pointing line of these elements are parallel to the reference element.

Some of the equipment that is used for alignment includes the transit and theodolite, used for measuring angles; clinometers, gunner's guadrant, and levels, used for measuring inclinations in the horizontal plane; and boresight telescopes and self-contained optics, used to establish the pointing line of equipment.

To have an accurate alignment, you should follow a sequence of steps. These include establishment of reference planes, placement of reference marks, establishment of parallelism between the RPPs of all equipment in the combat system, collimation of fire control radars, establishment of train and elevation zero, star checks, and the establishment of bench mark and tram reference readings.

This chapter is not intended to be a substitute for established alignment procedures; the actual alignment procedures that you use are contained in the appropriate combat system alignment OP for your ship.

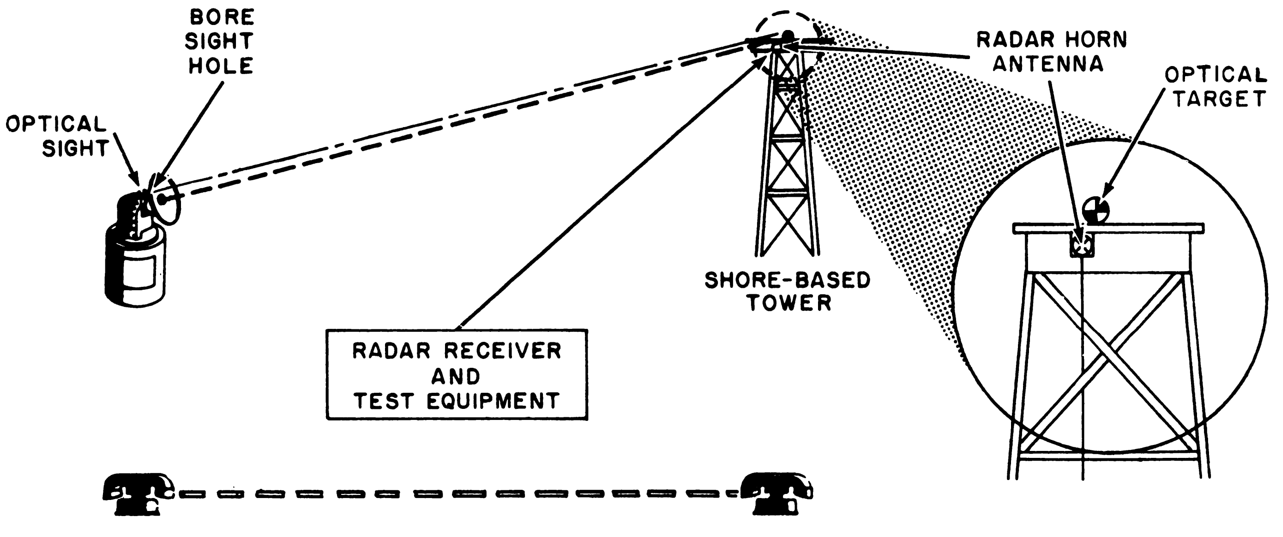
# CHAPTER 8

# COLLIMATION

In chapter 7 we mentioned that the collimation of fire control radars is one of the major steps toward achieving a successful battery alignment. *Radar collimation* is the parallel alignment of the radar beam axis and the optical axis of the radar antenna. This can be accomplished by using a shore tower, which supports an optical target and a radar horn antenna (fig. 8-1). The horn antenna is connected to rf power measuring equipment and is properly positioned in relation to the optical target. The horn antenna displacement, relative to the optical target, is determined by the relative displacement of the two axes (optical and rf) as measured at the radar.

The parallelism of the two axes is checked or adjusted by training and elevating the radar antenna until the cross hairs of the optical sight intersect the optical target. At this time, maximum rf energy should be directed into the horn antenna, as measured by the power measuring equipment. If it is not, the axes are not collimated, and appropriate adjustment procedures should be accomplished. In brief, this requires that one axis be aligned to the other until they are parallel. In this chapter, the theory of collimation, shore tower operation and requirements, and the test equipment used in collimation and correlation are discussed.

*Collimation* is an optical electronic technique used to establish parallelism between the rf beams radiated from a radar antenna or between the rf beam (or beams) and the optical line-of-sight axis of the antenna. This optical axis is normally



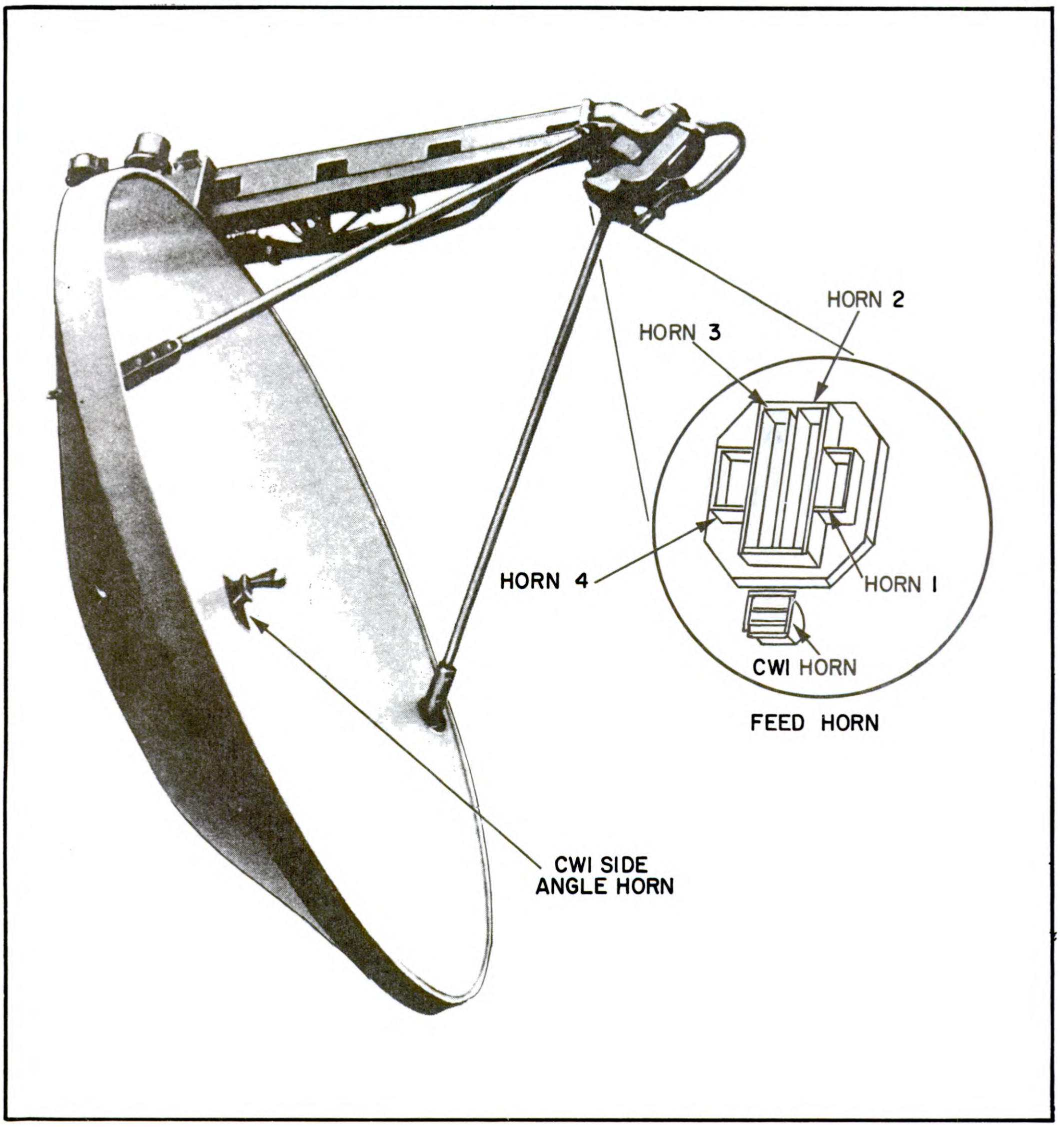
92.50

Figure 8-1.—Radar collimation.

called the boresight axis and is established with the optical telescope.

Optical telescopes (normally called borescopes or boresights) are usually permanently mounted on the radar antennas. For the TARTAR/TERRIER missile systems and Mk 86 FCS, the radar antennas are mounted on unmanned directors; while on older gunfire control systems, the telescopes are permanently mounted on manned directors. Besides their use in determining the director line of sight, these telescopes on the manned directors are also used during normal operations for target tracking.

The optical-line-of sight or boresight axis is the fixed reference for some radars, while for others, it is not. On those radars where the boresight axis is the fixed reference, the rf beam(s) of these radars is/are aligned to the boresight axis. On those radars where the boresight axis is not fixed, the telescope is moveable and adjusted parallel to the reference rf beam.



55.373

Figure 8-2.—TARTAR radar C-band and X-band feed horns.

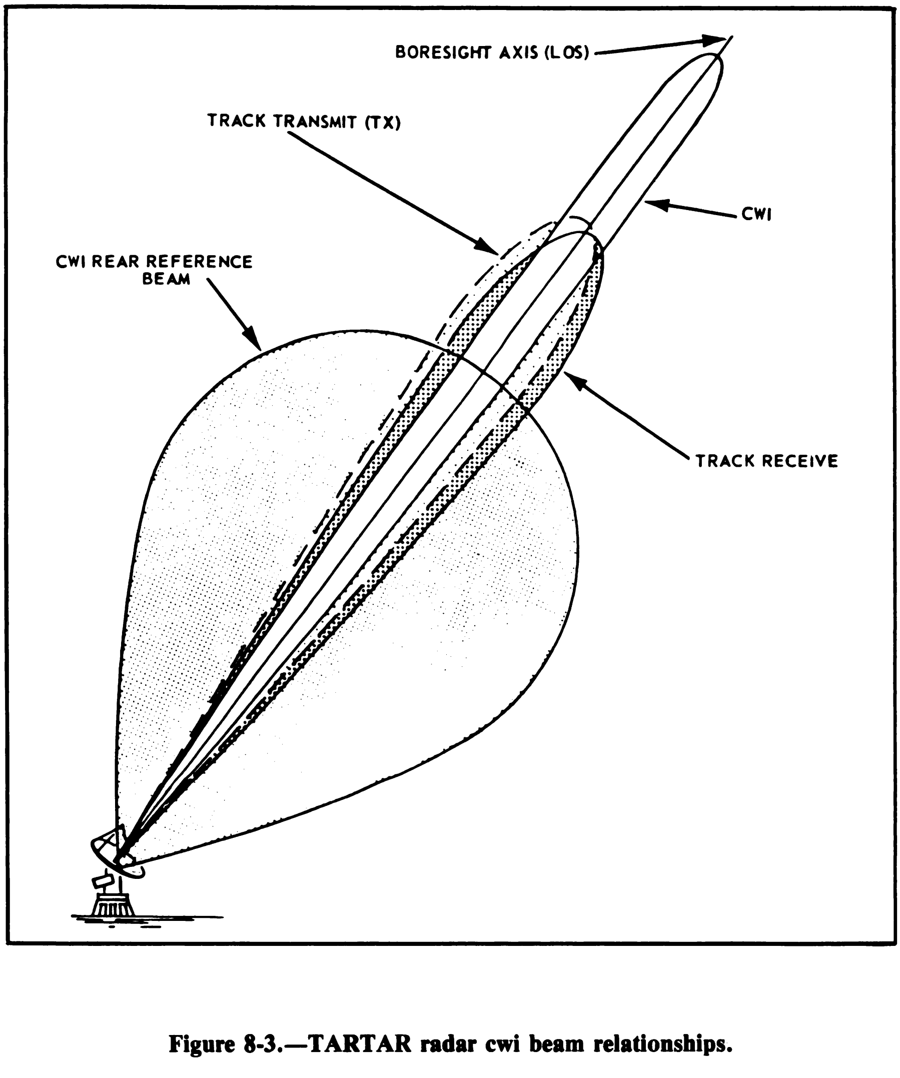
## RADAR COLLIMATION REQUIREMENTS

Because different types of radar are used in the missile and gun systems, the collimation requirements for each radar are different. In the following paragraphs, we discuss the requirements for the most commonly employed radar systems.

### TARTAR GUIDED MISSILE FIRE CONTROL SYSTEM (GMFCS) COLLIMATION REQUIREMENTS

The primary radar for the TARTAR missile system is the AN/SPG-51B/C/D. The AN/SPG-51B/C/D is an automatic target acquisition and missile guidance radar set that uses C-band pulsed-Doppler techniques for target tracking and an X-band continuous wave (cw) illuminator to provide guidance for the semiactive homing TARTAR missile.

As shown in figure 8-2, the C-band and X-band feed horns on the radar antenna are effectively located at the same feed point so that the track and cw illuminator rf beams are parallel, within specified tolerance. A wide cwi reference beam is also generated by the X-band horn, which is located in the center of the antenna reflector to fill in any nulls in the cwi main beam and to provide missile rear reference information. The beam relationships are shown in figure 8-3.



55.374

Figure 8-3.—TARTAR radar cwi beam relationships.

For rapid target acquisition and proper tracking, the track radar beam must be parallel to the boresight axis, which is referenced to the ship's weapons system by bench marks. An appreciable error between the axis along which the radar effectively receives the return pulses (called the track receive or TR axis) and the axis along which the radar transmit (called the track transmit or TX axis) reduces the rapid acquisition capability of the radar. An error between the TR axis of the tracking radar and the axis of the cw illuminator impairs TARTAR missile performance by reducing target illumination power.

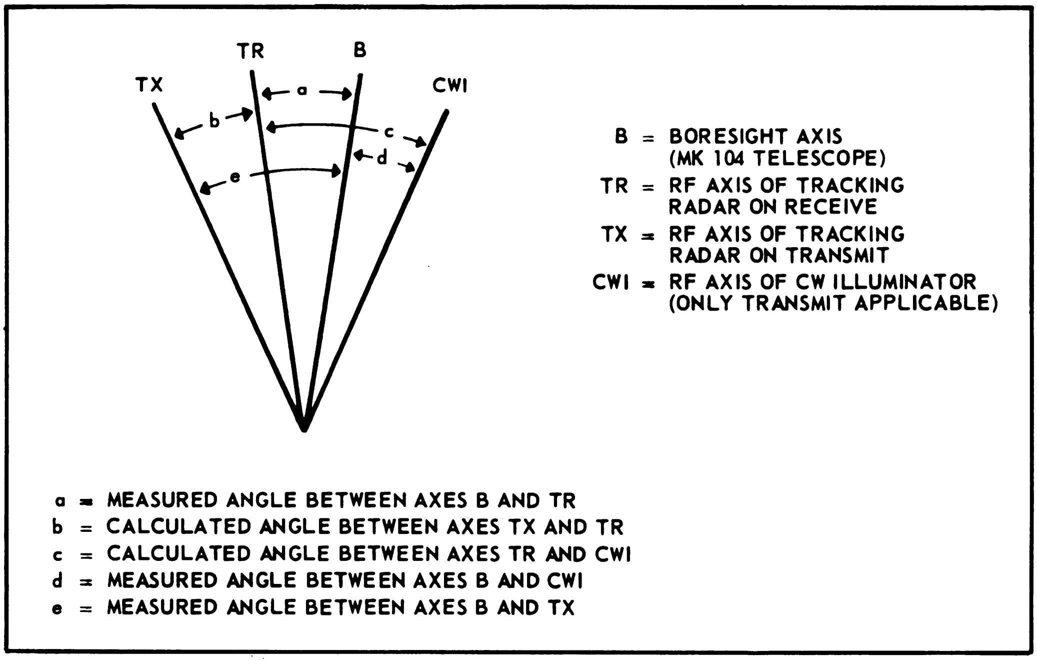
Collimation of the TARTAR radar consists of determining the error between the rf beam axis and the boresight axis and the errors between the rf beams themselves. The collimation axes are shown in figure 8-4.

In addition to determining the relative positions of the rf beam axes, collimation operations should ensure that the following requirements have been fulfilled:

- Angle error signals are generated properly in each quadrant when the antenna is off target axis.
- Specified angle error sensitivity of the angle tracking circuitry is obtained.
- Beam pattern is symmetrical. These collimation requirements are discussed later in this chapter.

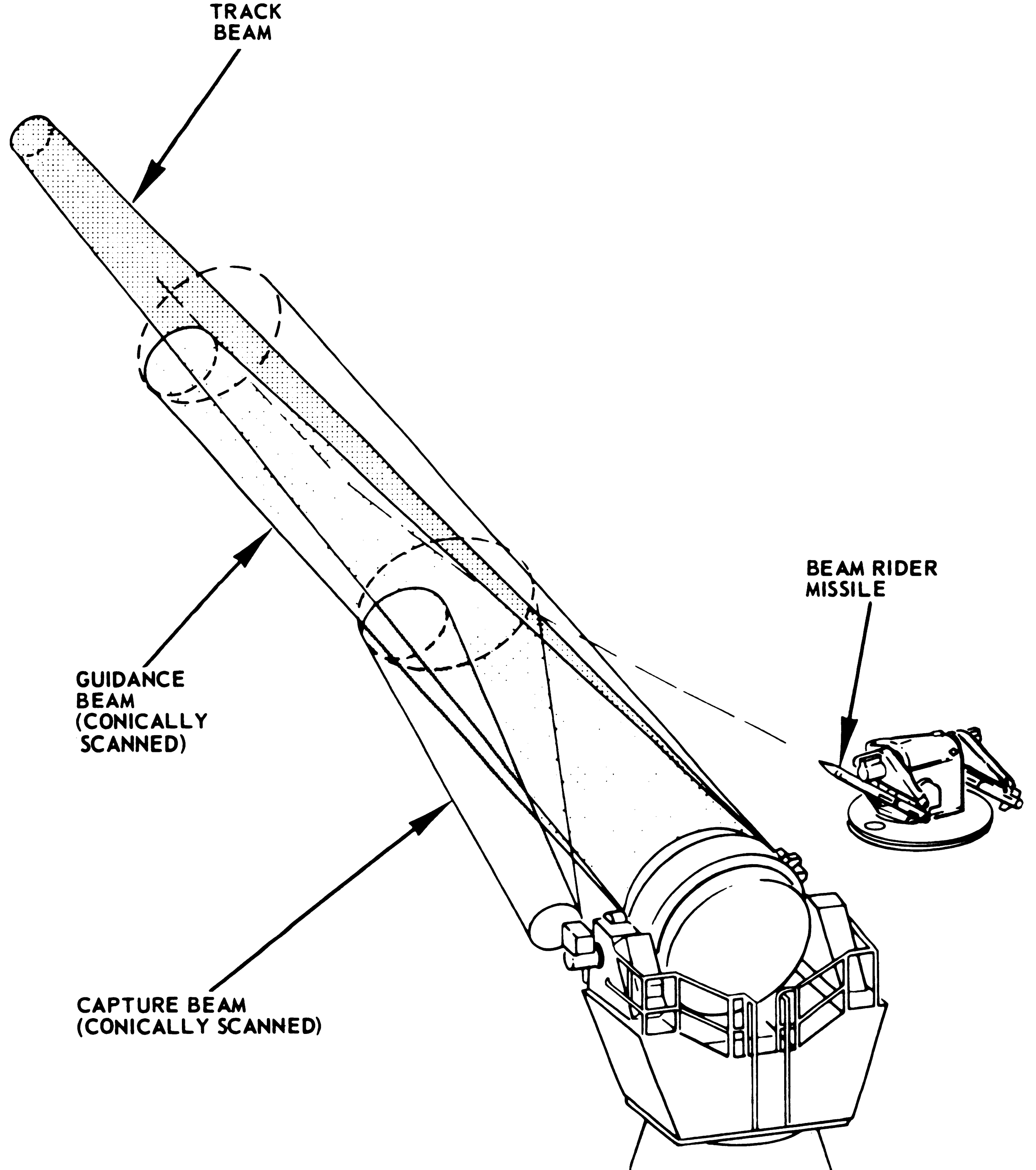
## TERRIER GMFCS COLLIMATION REQUIREMENTS

The TERRIER GMFCS uses the AN/SPG-55B radar set. The Radar Set AN/SPG-55B antenna assembly consists of two separate antennas—the main antenna, which provides the track beam, guidance beam, and cwi beam; and the capture antenna, which provides the capture beam. The track, guidance, and capture beam relationships are shown in figure 8-5, and the


TR
B
TX
CWI
a
b
c
d
e
B = BORESIGHT AXIS (MK 104 TELESCOPE)
TR = RF AXIS OF TRACKING RADAR ON RECEIVE
TX = RF AXIS OF TRACKING RADAR ON TRANSMIT
CWI = RF AXIS OF CW ILLUMINATOR (ONLY TRANSMIT APPLICABLE)
a = MEASURED ANGLE BETWEEN AXES B AND TR
b = CALCULATED ANGLE BETWEEN AXES TX AND TR
c = CALCULATED ANGLE BETWEEN AXES TR AND CWI
d = MEASURED ANGLE BETWEEN AXES B AND CWI
e = MEASURED ANGLE BETWEEN AXES B AND TX

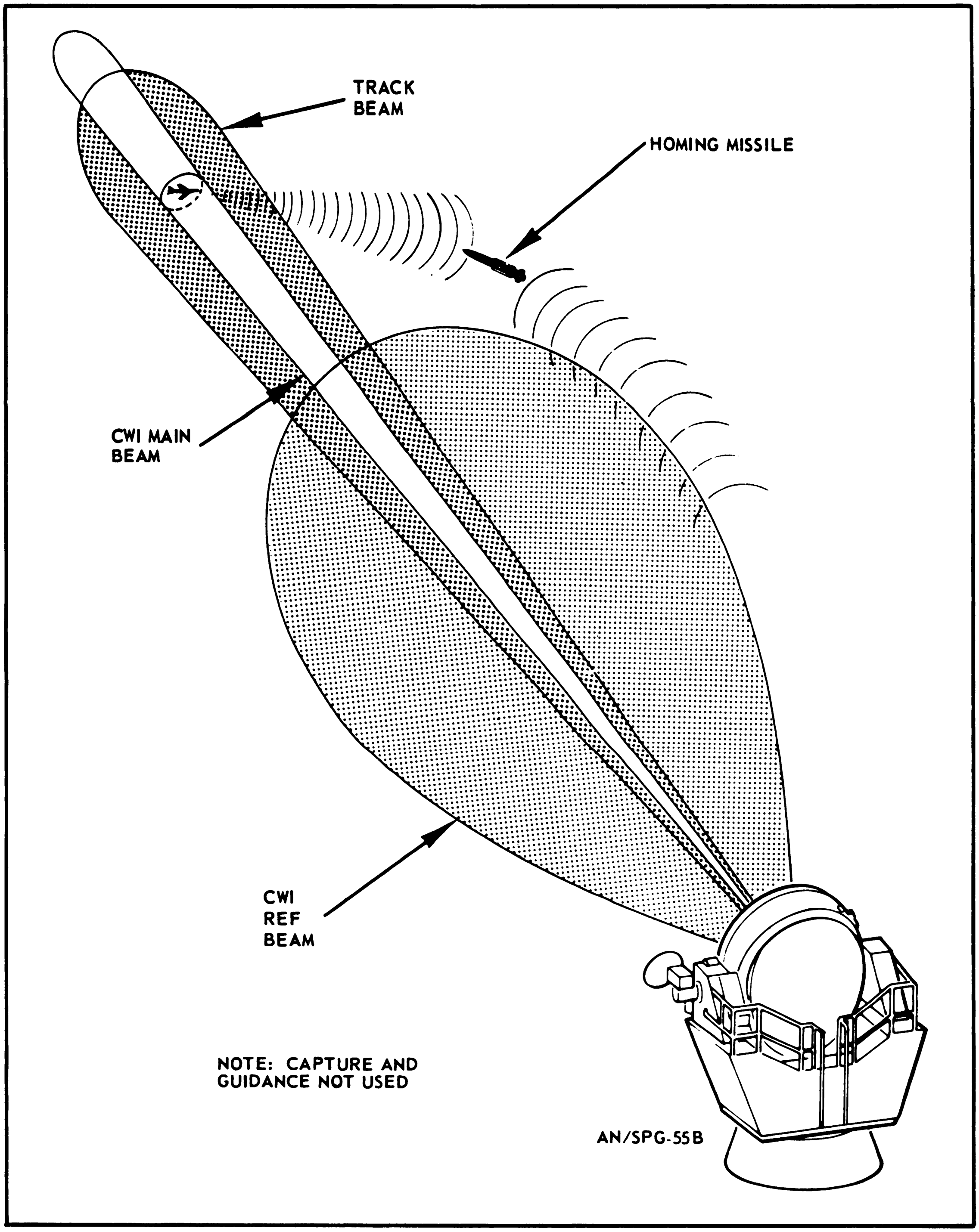
55.375

**Figure 8-4.—TARTAR radar collimation axes.**


TRACK BEAM
BEAM RIDER MISSILE
GUIDANCE BEAM (CONICALLY SCANNED)
CAPTURE BEAM (CONICALLY SCANNED)

55.376

**Figure 8-5.—TERRIER radar track, guidance, and capture beam relationships.**



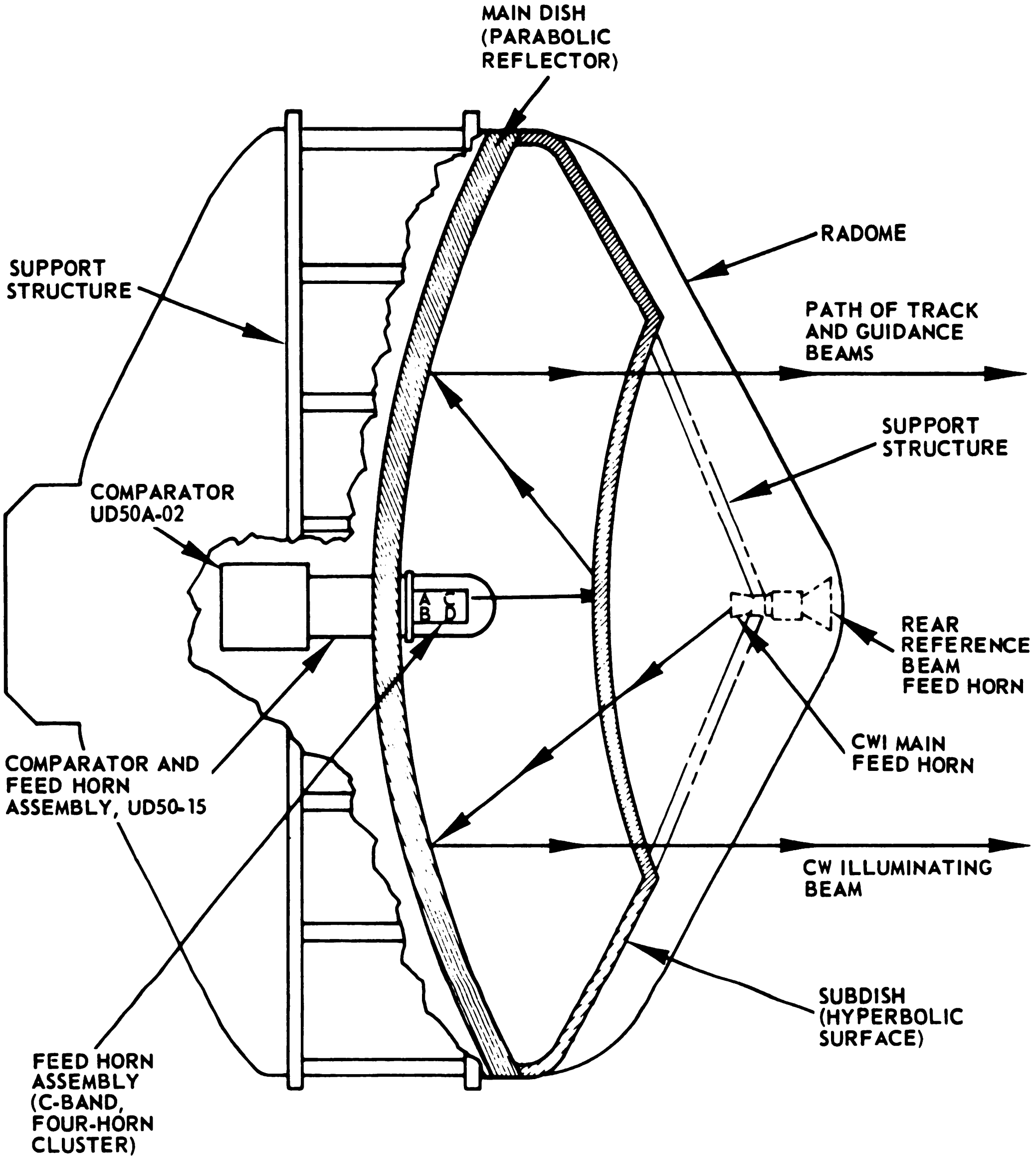
55.377

Figure 8-6.—TERRIER radar track and cwi beam relationship.

track and cwi beam relationships are shown in figure 8-6. The capture-guidance mode is employed for control of beam-riding missiles, and the track cwi mode is used for homing missiles.

The track and guidance rf share the same microwave components; thus, they should always be in collimation with each other. The main antenna, shown in figure 8-7, is a Cassegrainian type of antenna, which consists of a main dish, subdish, support structure, comparator, and feed horn assembly for C-band rf radiation. A back-to-back X-band feed horn assembly is mounted in front of the reflectors. The entire assembly is protected by a radome.

The main dish consists of a parabolic metal surface with a dielectric support grating of parallel wires. The parabolic surface acts as a rotational reflector that reflects either vertically or


MAIN DISH (PARABOLIC REFLECTOR)
RADOME
SUPPORT STRUCTURE
PATH OF TRACK AND GUIDANCE BEAMS
SUPPORT STRUCTURE
COMPARATOR UD50A-02
A C B D
REAR REFERENCE BEAM FEED HORN
CWI MAIN FEED HORN
COMPARATOR AND FEED HORN ASSEMBLY, UD50-15
CW ILLUMINATING BEAM
SUBDISH (HYPERBOLIC SURFACE)
FEED HORN ASSEMBLY (C-BAND, FOUR-HORN CLUSTER)

55.378

Figure 8-7.—TERRIER radar main antenna elements.

horizontally polarized incident rf energy. The incident rf, when reflected, is rotated 90°. The subdish consists of a hyperbolic dielectric surface with grating of horizontal wires. This surface reflects horizontally polarized rf energy but is transparent to vertically polarized radiation.

The feed horn assembly radiates horizontally polarized rf energy that is reflected by the horizontal wires of the subdish. The C-band energy is again reflected by the main dish and rotated 90° to vertical polarization. The vertically polarized C-band energy is then radiated through the subdish as a narrow beam.

The comparator forms track and guidance rf energy into the track and guidance beams and extracts range, elevation, and traverse information from each target return. The feed horn assembly consists of a C-band, four-horn monopulse cluster located at the vertex of the parabolic surface.

Guidance rf energy is generated by the guidance transmitter and shares the same feed horn assembly. It is radiated as a conically scanned beam.

The two X-band feed horns are mounted back to back near the focus of the parabolic surface. The X-band feed horn facing the main dish radiates vertically polarized rf energy. The subdish is transparent to this radiation, and the main dish reflects X-band energy as a narrow beam (cw illuminating beam). The X-band feed horn facing away from the main dish transmits X-band vertically polarized rf energy (rear reference beam) as a broad beam centered about the main cw illuminating beam.

The cw feed horn facing the main dish and the four horns of the feed horn assembly are cross polarized, thereby reducing incident X-band radiation on the C-band, four-horn cluster. In addition, low pass filters inserted in all the microwave channels leading to the receiving system effectively filter out any X-band signals superimposed on C-band signals.

The capture antenna subassembly, shown in figure 8-8, is a Cassegrainian type, consisting of a circular waveguide feed horn, a polarized parabolic reflector, and a polarization converter.

The circular waveguide feed horn operates in the transverse electric ($TE_{11}$) mode. The feed horn is skewed at a preset angle from the boresight to produce a circular symmetrical beam pattern. The rf energy emitted from the feed horn is vertically polarized. The rotation pattern is such that the phase front of the radiated energy is not affected during rotation. Therefore, the radiated energy from the feed horn, which is incident on the parabolic reflector, is still vertically polarized.

The parabolic reflector serves as a vertically polarized focusing radome. Therefore, horizontally polarized energy is reflected and only vertically polarized energy is transmitted. Since the rf energy from the feed horn is horizontally polarized, the radome reflects and focuses this incident energy into the polarization converter.

The polarization converter consists of metal plate polarization grids, which are one-quarter wavelength (C-band frequency) in thickness and bonded to the surface of the plate. The polarization grids are oriented at an angle of 45° to the incident energy.

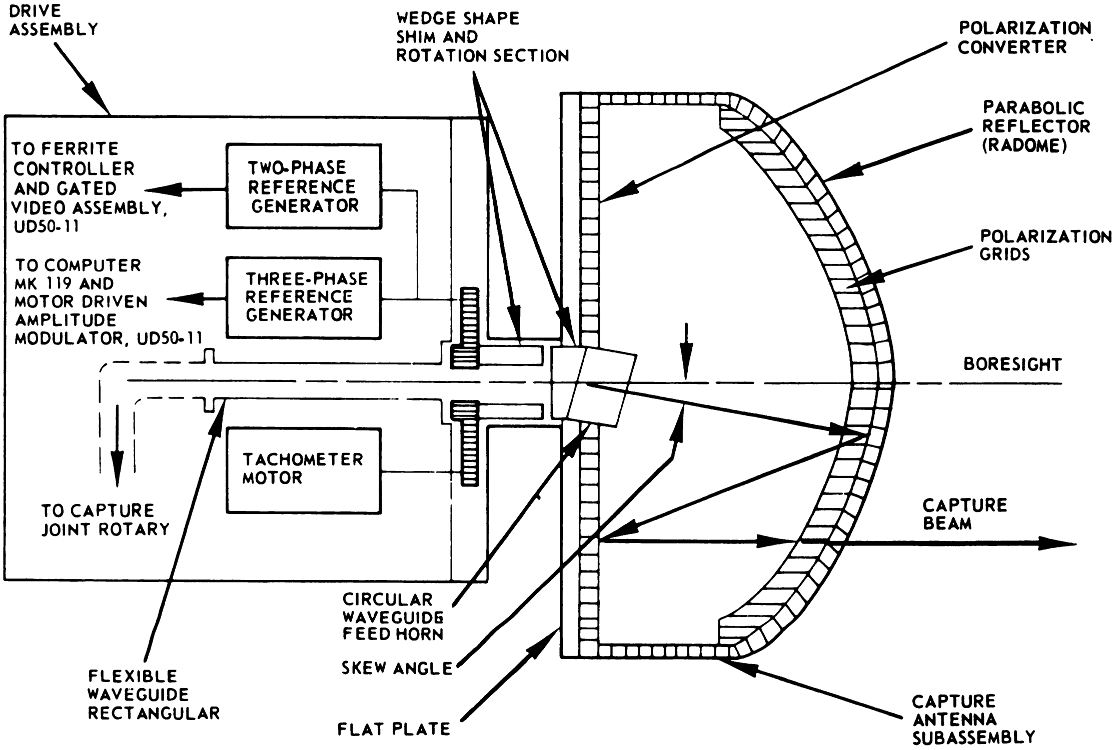
The operation of the polarization converter is identical to the polarization converter of the main antenna assembly. Therefore, the horizontally polarized incident energy is reflected as vertically polarized energy and transmitted through the radome as the capture beam.

The use of two interlocking radars in the TERRIER beam-riding missile system requires a much broader spectrum of rf parameter than a system that uses a single radar. A complete listing of the critical rf parameters is too numerous to include here, but some of the parameters that can be determined and measured by use of the shore tower and its associated test equipment include checking proper modulation slopes in the capture and guidance axes, correct AM/FM phasing between the capture and guidance axes, and rf power density (to determine if the rf power radiated is sufficient for missile control).

You should understand how a misalignment of rf parameters can affect your radar's tracking ability. For example, when the missile is at some place in the beam other than BZI (beam zero indication), it receives orders to correct itself and move to the center of the beam. When the system has a small phasing error, the missile moves toward where it thinks the center should be; but, in fact, it moves in a spiral around the BZI, resulting in an increase in miss distance. The miss distance will be increased with an increase in phase error, and a large phase error will result in the missile flying away from the beam.

When capture-to-guidance beams are not collimated, the changeover from capture to guidance will be rough, and the missile may be lost if the error is too large. If the guidance and track beams are not collimated, the miss distance is directly affected and increases with range. When cwi-to-track axes are not collimated, the illuminator power on the target is reduced; therefore, the missile range capability is reduced.

An overview of collimation procedures is covered later in this chapter, but first you'll need to have an understanding of the collimation tower and the associated test equipment used with the tower.

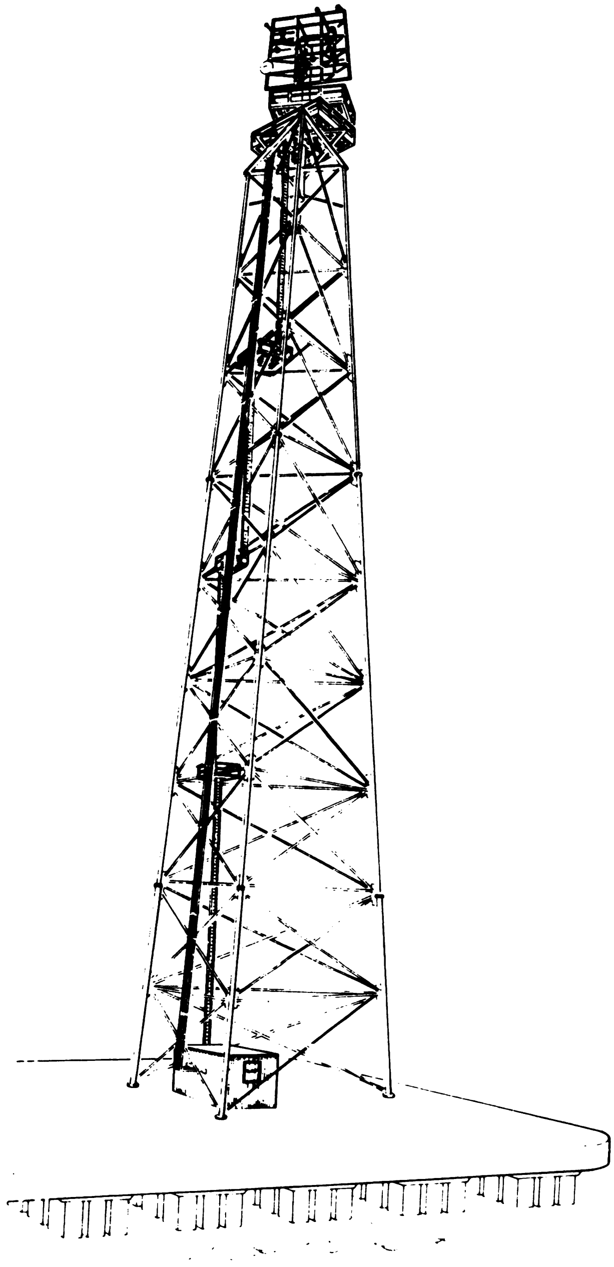

DRIVE ASSEMBLY
WEDGE SHAPE SHIM AND ROTATION SECTION
POLARIZATION CONVERTER
PARABOLIC REFLECTOR (RADOME)
TO FERRITE CONTROLLER AND GATED VIDEO ASSEMBLY, UD50-11
TWO-PHASE REFERENCE GENERATOR
TO COMPUTER MK 119 AND MOTOR DRIVEN AMPLITUDE MODULATOR, UD50-11
THREE-PHASE REFERENCE GENERATOR
POLARIZATION GRIDS
BORESIGHT
TACHOMETER MOTOR
TO CAPTURE JOINT ROTARY
CAPTURE BEAM
CIRCULAR WAVEGUIDE FEED HORN
SKEW ANGLE
FLAT PLATE
FLEXIBLE WAVEGUIDE RECTANGULAR
CAPTURE ANTENNA SUBASSEMBLY

55.379

**Figure 8-8.—TERRIER radar capture antenna subassembly.**

## RADAR COLLIMATION SHORE TOWER

Radar collimation shore towers (fig. 8-9) are designed primarily to check antenna beam collimation and rf characteristics of guided missile fire control systems. They also provide facilities for collimation and beacon checks of gunfire control radars and rf alignment (azimuth only) of the three-coordinate search radars.



55.380

Figure 8-9.—Collimation tower.

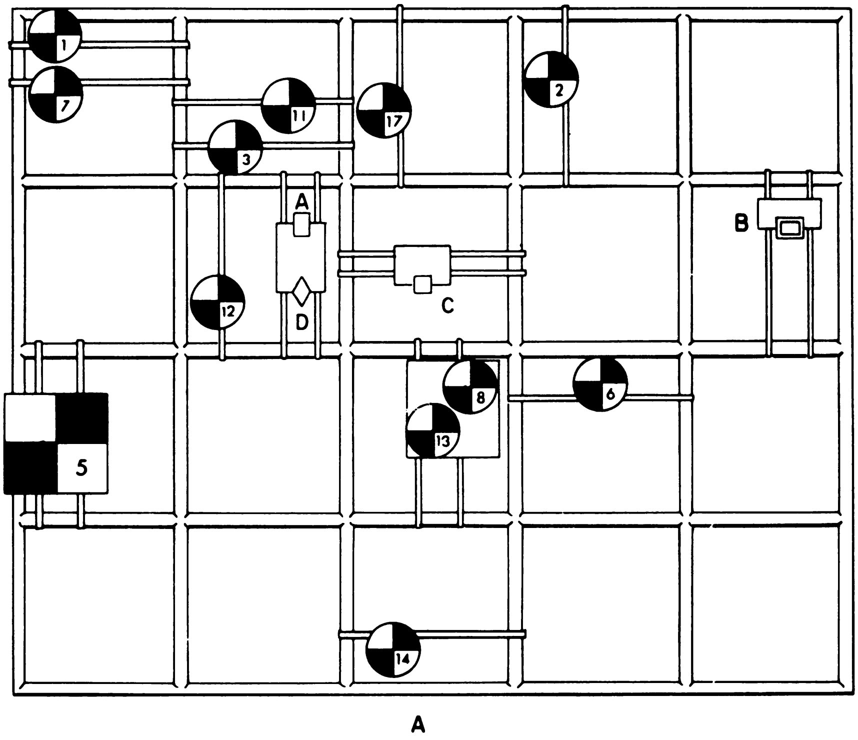
A radar collimation shore tower is a structure 130 to 250 feet high with a moveable array on which test antennas and associated optical targets are mounted. Waveguide and coaxial transmission lines connect the antennas on the tower array to an equipment room located at the base of the tower. The equipment room contains all test equipment necessary to perform collimation and check rf characteristics on the various guided missile/gunfire control radars and three-coordinate search radars found in the fleet.

### TOWER ARRAY

A tower array is shown in figure 8-10. The tower array can be moved in train and elevation by either powered or manual means. The array consists of a metal frame (usually constructed from aluminum piping) and test antennas and optical targets required for shore tower checkout of shipboard radars. The test antennas and optical targets are mounted on the metal frame and spaced to correspond to the spacing between the center of radiation (rf axis) and the telescope or boresight axis of each shipboard radar. This eliminates parallax errors caused by the small ship-to-tower distance involved during normal tower operations. The targets are illuminated by either back lighting or floodlights. The four test antennas and their characteristics, the associated optical targets, and the applicable radar systems that can be tested are summarized in figure 8-10.

### COLLIMATION TEST EQUIPMENT

Each tower is equipped with a set of test equipment for specific tower use. This equipment is stowed in the tower equipment room. The major items include Radar Test Set AN/SPM-9, Range Calibrator Set AN/UPM-115, Range Calibrator Set AN/SPM-6 Series, Radar Beacon Test Set AN/TPN-7 or AN/UPN-32, Continuous Wave Acquisition and Track (CWAT) tower transponder, and Microwave Power Meter HP 430 series.



ARRAY USAGE

| SYSTEM | RADAR | BEAM | ANTENNA | TARGET |
|---|---|---|---|---|
| TERRIER | AN/SPG-55 | GUIDANCE | A | 1 |
| | | CAPTURE | A | 2 |
| | | TRACK | A | 1 |
| | | CWI | D | 7 |
| | | CUSTER | B | 3 |
| | | DOPPLER | B | 1 |
| TARTAR | AN/SPG-51 | TRACK | C | 6 |
| | | CWI | D | 8 |
| | | TV | | 5 |
| MK68 | AN/SPG-53 | TRACK | D | 14 |
| | | CWI | D | 14 |
| MK86 | AN/SPG-60 | TRACK | D | 13 |
| | | TV | | 17 |
| MK92 | | TRACK | | 11(STR IN LINE) |
| | | | | 12(CAS) |
| | | | | 13(STR MK104) |
| | | TV(IF INTL) | | 17 |

TEST ANTENNAS

| ANTENNA | MODEL | GAIN | POLARIZATION | TYPE |
|---|---|---|---|---|
| A | AV4517 OR 56C1 | 18 db | VERTICAL | C-BAND HORN |
| B | MICROLAB/ FXR X638A | 22 db | VERTICAL | X-BAND HORN |
| C | AV4517 OR 56C1 | 18 db | HORIZONTAL | C-BAND HORN |
| D | AEL H6000 | 8.2 db | CIRCULAR | X-BAND HORN |

B

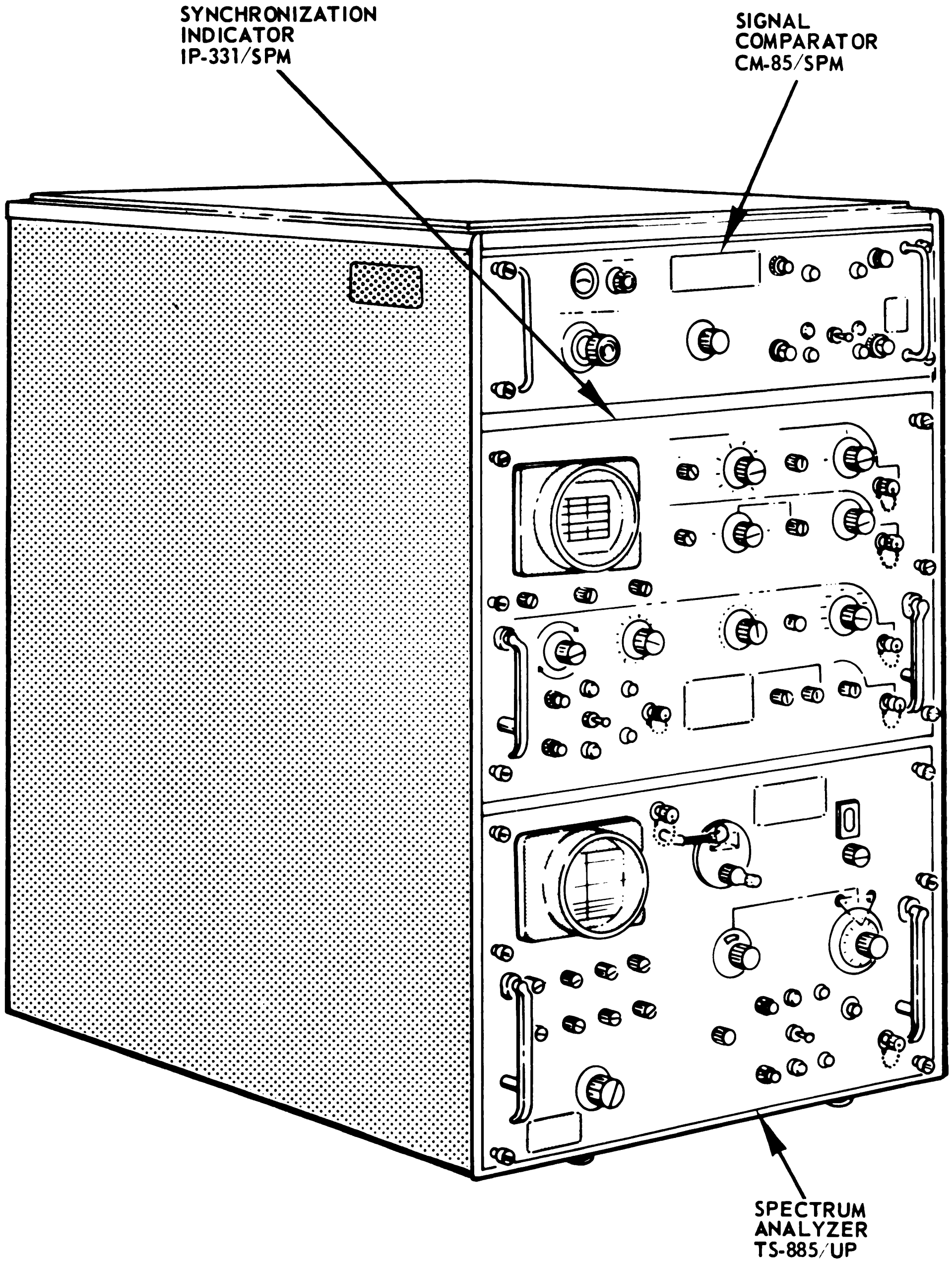
55.381

Figure 8-10.—(A) Standard tower array (B) array usage.

A number of additional items of general-purpose test equipment such as oscilloscopes, signal generators, coaxial cables, directional couplers, and variable attenuators are used at the tower and ship. Only the major items are discussed here.

### Radar Test Set AN/SPM-9

Radar Test Set AN/SPM-9 (fig. 8-11) is used to analyze missile guidance radars or pulsed radar rf signal characteristics. It is primarily used at the shore tower for analysis of TERRIER beam-riding


SYNCHRONIZATION INDICATOR IP-331/SPM
SIGNAL COMPARATOR CM-85/SPM
SPECTRUM ANALYZER TS-885/UP

55.382

Figure 8-11.—Radar Test Set AN/SPM-9.

radar parameters. The test set contains three chassis: a spectrum analyzer, a synchronization indicator, and a signal comparator.

The spectrum analyzer of the radar test set is capable of displaying separately (on a cathode-ray tube screen) the rf spectrum of the first, second, or third pulse of a coded pulse group, or the combined spectrum of all of the pulses. From such a spectrum display, measurements can be made of frequency, side lobe amplitude, and frequency pulling. It is also possible to determine that all of the desired pulses are present in the code group. In addition to its normal function of spectrum analysis, the spectrum analyzer detects the rf signal and preamplifies the resultant video information (pulses), and then presents this information to the synchronization indicator.

The synchronization indicator is used in Radar Test Set AN/SPM-9 as an oscillosynchroscope or as a conventional oscilloscope. The display on the screen of the indicator makes it possible to observe and measure the following pulse characteristics: rise time, decay time, pulse top flatness, pulse shape, pulsewidth, pulsewidth jitter, pulse code spacing, and pulse code jitter. Missing pulse groups can be detected when using a slow-sweep frequency. The indicator is used with the spectrum analyzer video preamplifier and precision attenuators to measure pulse AM, absolute and relative pulse power, and noise. A calibrator unit in the spectrum analyzer provides a standard square wave signal for calibration of the spectrum analyzer and synchronization indicator circuits, which are used for power measurement.

The signal comparator contains a precision resolver and FM detection circuits used with the synchronization indicator for measurement of AM to FM phasing. The comparator also contains a function selector that is used to determine the mode of operation of the radar test set.

### Range Calibrator Set AN/SPM-6 Series and AN/UPM-115

The Range Calibrator Set AN/SPM-6 series and AN/UPM-115 were designed primarily to check the accuracy of range indicators (scopes) used in C-band radar systems. In the shore tower application, however, their function is to provide video pulses, which act as simulated targets, to the shipboard radar. The range calibrator transmits an rf pulse identical to the one received when triggered by a radar pulse. By range gating one of the returned pulses, the shipboard fire control radar can track the tower. The Range Calibrator Set AN/SPM-6 series (shown in fig. 8-12) is used

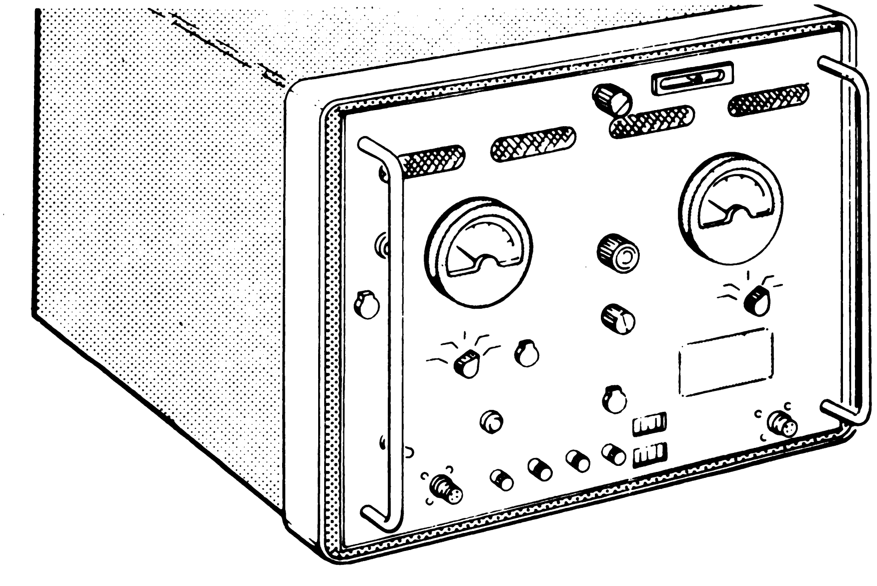


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Figure 8-12.—Range Calibrator Set AN/SPM-6 series.

for short pulse radars, while the Range Calibrator Set AN/UPM-115 (shown in fig. 8-13) is used for the TERRIER Radar Set AN/SPG-55B in the 1 PC (pulse compression) mode.

### Continuous Wave Acquisition and Track (CWAT) Transponder

The CWAT tower transponder (fig. 8-14) is basically a biphase (0-180°) modulator. Incident power radiated by the CWAT transmitter is received from the cwi horn, passed through the modulator, and reradiated out the CWAT horn. The modulation waveform for a clean target is an 80-kHz square wave, which results in a suppressed carrier spectrum with only odd harmonics of the 80-kHz modulation function. In addition, a jamming signal is provided that has a 20-kHz modulation bandwidth offset from the carrier by 80 kHz. The CWAT tower transponder is used during collimation to determine Doppler track boresight and to measure Doppler track angle sensitivity.

### Microwave Power Meter

The microwave power meter (fig. 8-15) is a portable test instrument used during collimation for establishing cwi beam boresight, cluster horn beam boresight, and measuring cwi power density. The power meter operates on 115 or 230 vac ± 10 percent, 50 to 400 Hz, 2.5 watts. The set provides full-scale readings from 0.01 (−20 dBm) to 10 milliwatts (+10 dBm) in seven ranges, range

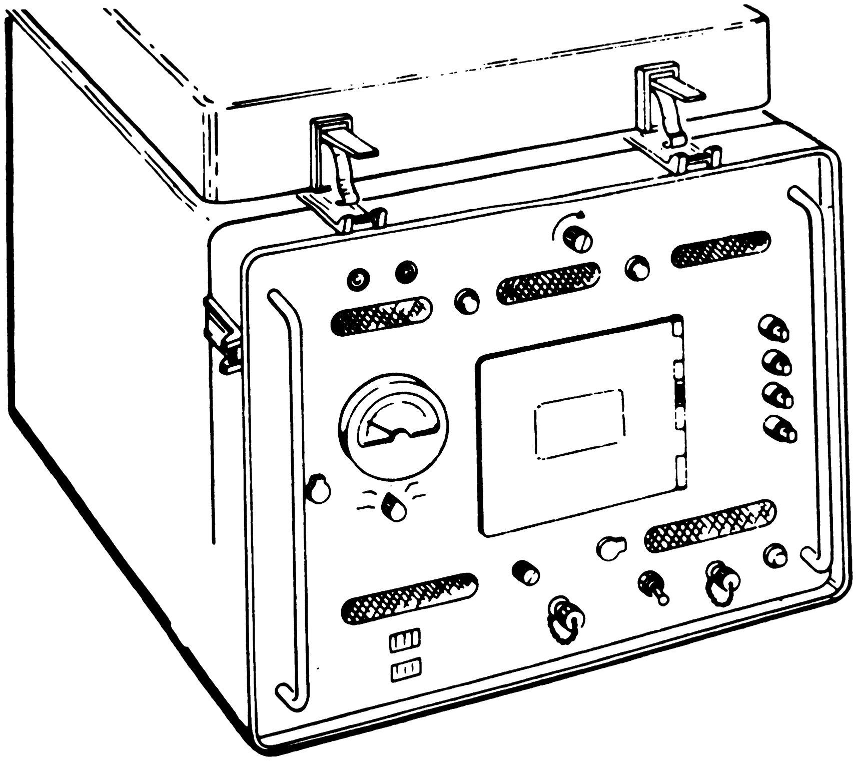

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Figure 8-13.—Range Calibrator Set AN/UPM-115.

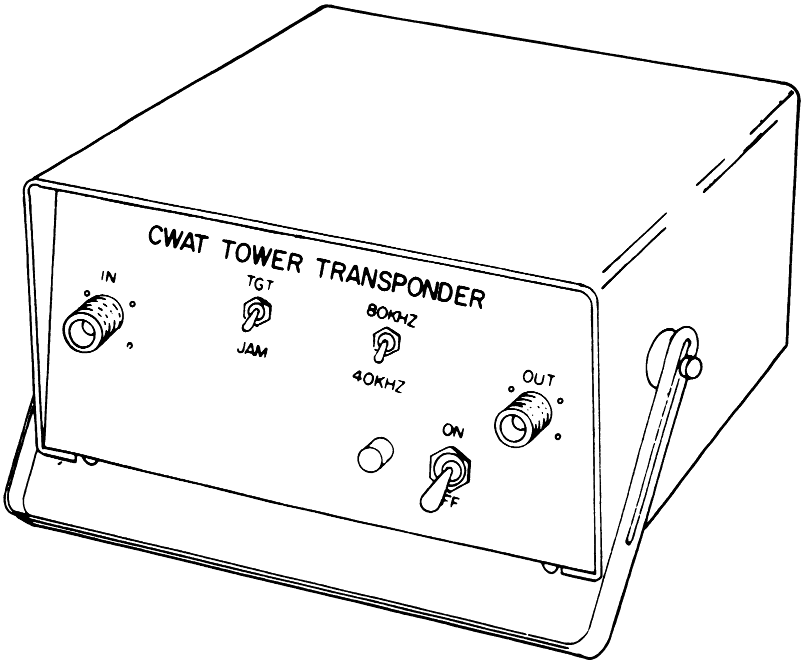

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Figure 8-14.—CWAT tower transponder.

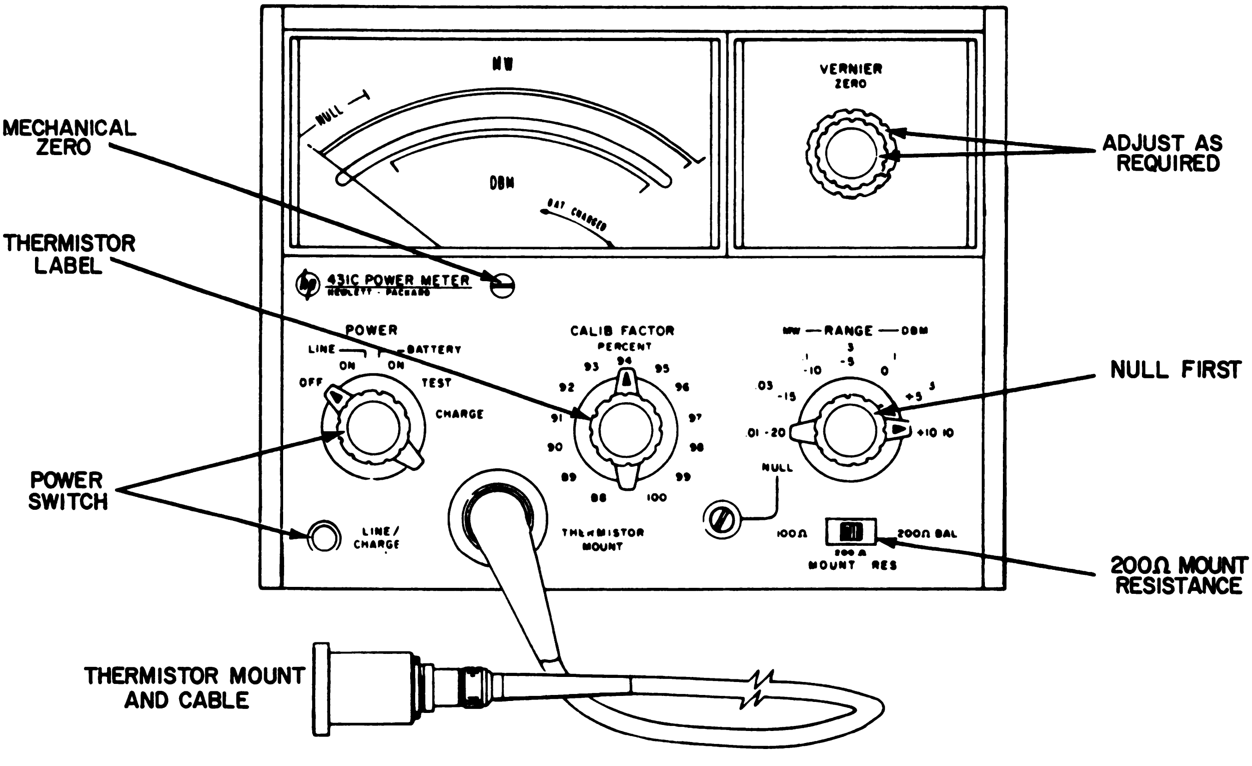

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Figure 8-15.—Microwave power meter.

switching in 5-dB steps, and taut-band meter measurement with mirror-backed scale. The set is calibrated in milliwatts and dBm and is used in the 10-mHz to 10-gHz frequency band.

### Radar Beacon Test Set AN/TPN-7

The Beacon Set AN/TPN-7 (fig. 8-16) is a portable X-band beacon set designed primarily to serve on shore as an accurate reference point for the control of ship-to-shore gunfire. When it receives a short duration pulse of rf from an associated fire control radar, the beacon responds with a coded reply pulse. Reply pulses are transmitted only as long as interrogating signals are received. When the reply pulses are received by the interrogating radar, they appear as video pulses on the radar range scope. The first pulse of each reply is a range pulse that may appear along or be followed by any one of six combinations of coded pulses. The set is used at the shore tower for beacon checks and collimation for gunfire control system radars.

## COLLIMATION PROCEDURES

Shore tower checks between regular overhaul periods are generally not performed except when NAVSEA or Naval Ship Weapon Systems Engineering Station (NSWSES) specifies a shore tower check as a result of extensive shipyard or

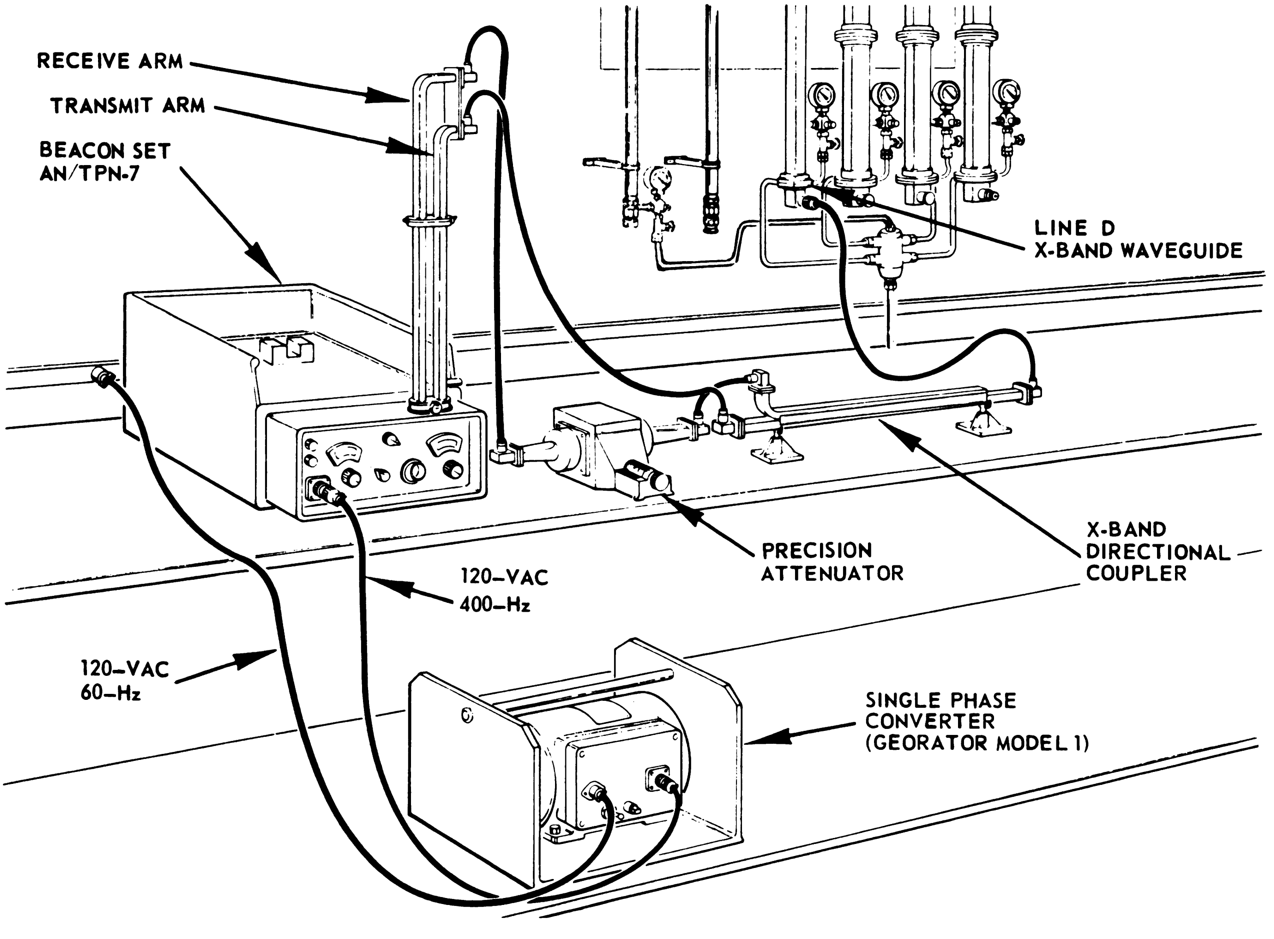

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Figure 8-16.—Beacon Set AN/TPN-7.

alteration work, or after a microwave casualty occurs that requires microwave component replacement. Also, on those ships outfitted with a portable ship's tower, the need for shore tower service is established when ship tower checks indicate that tolerances are exceeded or correlation data is in question.

Certain environmental condition requirements must be complied with prior to tower operation. These include the amount of ship motion and the weather conditions under which the collimation procedures are performed.

Because ships must be tested while afloat, certain methods of limiting the motion are used. One method consists of securing the ship snugly to a pier or dock or, in certain cases where excessive ship motion is created because of tide changes, by using various weighting methods, as shown in figure 8-17, to reduce the ship's motion. The weather condition must be considered because of the adverse effects it can have upon collimation tests. Other conditions affecting these tests are visibility between ship and tower, wind and water conditions, and heat radiation. Visibility should be good between the ship and tower. High winds or rough water conditions can cause ship motion to be so excessive as to invalidate test results. Should refraction due to heat radiation be observed while viewing an optical target, consideration should be given to rescheduling

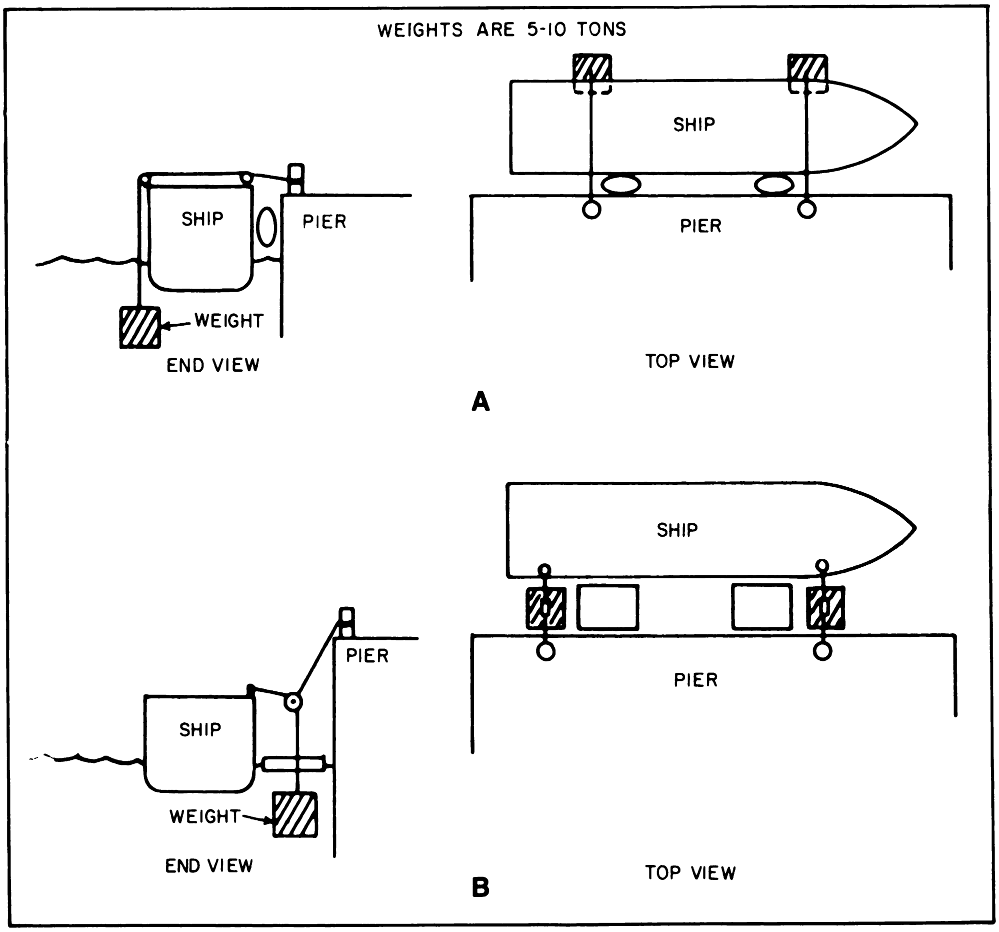

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Figure 8-17.—Ship weighting for reducing motion.

operations at an earlier hour of the following day.

## TARTAR COLLIMATION PROCEDURES

The TARTAR weapon system is employed aboard several classes of ships. Each class of ships has a unique configuration of the weapon system components. Consequently, each class has its own specific collimation procedures. The collimation procedures discussed here are of a general nature and do not address specific procedures for any particular class of ships.

### Track Receive (TR) Axis Collimation

The angle error null method of measurement is the method used to determine the error between the track receive axis and the borescope axis of AN/SPG-51B/C/D. At the shore tower, the Range Calibrator Set AN/SPM-6 series is connected to transmission line C, which connects to antenna C on the tower array. Aboard ship, the AN/SPG-51 director is manually pointed toward the shore tower. The director is not energized during any AN/SPG-51B/C/D collimation checks. When the director is in the required position, the AN/SPG-51B/C/D track transmitter is set to RADIATE, thus triggering the AN/SPM-6 series at the shore tower. When triggered by the radar signal, the AN/SPM-6 series begins transmitting back to the radar set rf pulses identical to the pulses being received, which, when received by the radar, appear as target video on the A-scope of the radar operator's console. Only three to five of these video pulses are observable on the A-scope because of the high prf of the radar set.

The radar is placed in range track when video pulses are observed on the A-scope. This is accomplished by gating one of the returned pulses. A Doppler target is required to ensure that an angle error output voltage is generated whenever the antenna (director) is manually moved off target. This requirement is accomplished by setting the CLUTTER REJECT switch on the operator's console to 0 KT position. The traverse and elevation angle error voltages generated from the angle error detector module of the AN/SPG-51B/C/D data converter are monitored by two voltmeters.

With the radar in track, the director is held stationary on target (brakes set) in one axis (TRAIN or ELEVATION) and rocked through the angle error null point (as indicated by the vtvm) in the other axis. The mark method is used to correlate angle error null voltage readings with borescope readings. The borescope readings (in mils) are taken with respect to the AN/SPG-51B/C/D track radar optical target 6 or 10 on the tower array. A minimum of 20 nulls and the borescope readings are taken to determine the collimation error between the TR axis and the borescope axis. This procedure is then repeated for the other axis (traverse or elevation).

Before actually determining the TR axis error by the angle error null method, checks are made to determine that an angle error of proper sensitivity (1 v/mil) can be generated in each quadrant and that conical scan, receive only (COSRO) phasing is correct (minimum crosstalk) to preclude offset of the angle error null.

### Track Transmit (TX) Axis Collimation

The beam-pattern plot method of measurement is the method used to determine the error between the track transmit axis and the borescope axis of the Radar Set AN/SPG-51B/C/D. There is no requirement for test equipment aboard ship during the performance of this test. The test setup aboard ship consists of placing the track transmitter in the RADIATE mode, pointing the radar antenna (director) toward the shore tower, and centering the AN/SPG-51B/C/D track radar optical target 6 or 10 in the borescope (Telescope Mk 104).

In the tower, the average power meter is connected through the calibrated attenuator (C-band) to the waveguide line connected to antenna C on the array. Attenuation is adjusted to allow the track transmitter power to be read conveniently on the power meter (in decibels or milliwatts as preferred). After establishing a reference point (reading of maximum power) by coaching the director operators aboard ship via sound-powered telephone, the track transmitter output power is plotted at the tower as the antenna (director) is held stationary in one axis (traverse or elevation) and moved off target in the other axis. The offset readings in mils are given by the borescope observer aboard ship.

Usually, a 30-mil excursion each side of the maximum power point is sufficient. After plotting the power readings to offset in mils on a graph, a horizontal line connecting the half-power points (3 decibels down) is drawn. By bisecting this line and observing where the bisecting line intercepts the mils axis, the collimation error between the TX axis and the boresight axis is determined. Extreme care must be exercised in taking each power reading to obtain accuracy with this method. The borescope operator may have to give several marks at each offset position to obtain a good average power reading. The TX axis beam-pattern plot-method graph is shown in figure 8-18.

### CWI Axis Collimation

The beam-pattern plot method of measurement is the method used to determine the error between the cwi axis and the borescope axis of Radar Set AN/SPG-51B/C/D. There is no requirement for test equipment aboard ship during the performance of this test. The procedures for determining cwi axis error are similar to those for the track transmit axis except that the cwi radar is used.

The test setup aboard ship consists of placing the cwi transmitter in RADIATE, pointing the radar antenna toward the tower, and centering the cwi optical target 8 in the borescope.

In the tower, the average power meter is connected through the calibrated attenuator (X-band) to the X-band waveguide line going to antenna D on the tower array. The attenuator is adjusted to allow the cwi power to be read conveniently

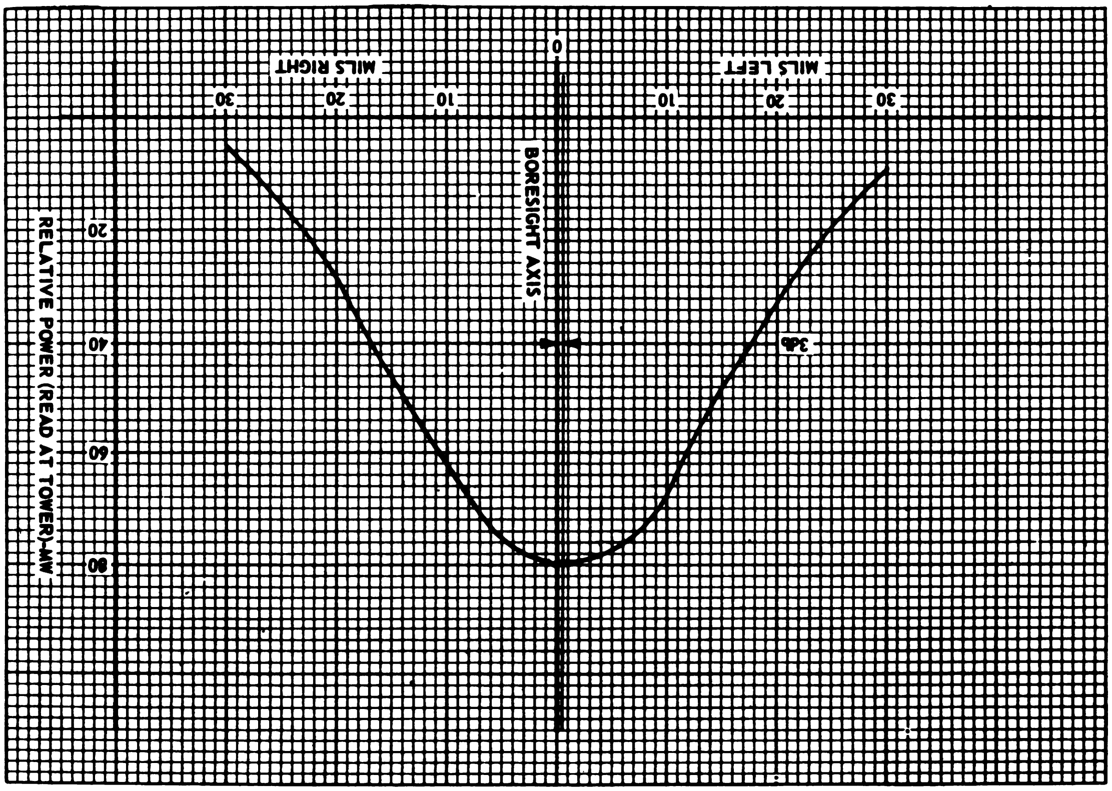

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Figure 8-18.—Beam-pattern plot-method graph.

on the power meter (in decibels or milliwatts as preferred). After establishing a reference point (maximum power reading) by coaching the director operators aboard ship, cwi power is plotted at the tower as the antenna (director) is held stationary in one axis (traverse or elevation) and moved off target in the other axis. The offset readings in mils are given by the borescope observer aboard ship.

A power plot curve is drawn and the 3 decibel down points are connected by a horizontal line. The bisector of this line will intercept the mils axis of the graph to provide the collimation error similar to the TX procedures. Usually, a 15-mil excursion each side of the maximum power point is sufficient.

After all three rf beam axes have been established, their data is plotted together on a beam position summary graph as shown in figure 8-19. From their relative positions, the collimation errors can be determined and corrective action, if required, can be made.

## GFCS MK 68 COLLIMATION

Aboard ship, the GFCS Mk 68 is placed in the NORMAL MODE, and control of director train and radar elevation is transferred to the Radar Set AN/SPG-53 control console. The director is locked in crosslevel by use of the crosslevel lock pin. Caution must be taken not to energize the crosslevel drive while the director is stowed in the crosslevel position. The director is then pointed toward the shore tower so that target 14 on the tower array is observed in the reticle circle of the Tracker Telescope Mk 100.

In the shore tower, the Beacon Set AN/TPN-7 or AN/UPN-32 is energized and its receiver frequency is set to midband. The beacon transmitter frequency is set midway between the receiver frequency and either end of the transmitter bandpass.

At the radar set aboard ship, the beacon cavity tuning control is set 59 MHz above the transmitter frequency setup on the AN/TPN-7 or AN/UPN-32. On the radar console, the receiver tuning selector switch is set to BEACON and the scan control switch to AUTO. The radar transmitter frequency is tuned until a response signal from the AN/TPN-7 or AN/UPN-32 is observed on the radar indicator scopes. Various codes are selected at the AN/TPN-7 or AN/UPN-32 to ensure that the beacon signal on the radar scope is positively identified. When identified, the code control switch of the beacon set is set to 0 for the remainder of the operation.

The director is trained and the radar elevated until the beacon signal is maximized and in the range notch on the radar indicators. The GFCS is then placed in TRACK on the beacon signal.

With the director in track on the beacon signal, target 14 is observed through the Tracker Telescope Mk 100. If the target is centered in the reticle circles, the radar rf axis is collimated satisfactorily to the director optical axis. If not, it indicates a collimation error that must be corrected by mechanical adjustment of the radar antenna. Procedures for adjustment are contained in the equipment publications.

## TERRIER COLLIMATION PROCEDURES

The basic reference for most tower tests is the Radar Borescope Mk 115. The initial step in TERRIER collimation is to assure that the borescope is set properly. Experience indicates that over a period of time the borescope tends to become slightly uncollimated. However, as the borescope is the only reference to tie the radar to the ship bench mark for battery alignment procedures, the borescope should not be realigned after shipyard alignment unless several tests over a period of time have shown it to be more than 0.5 mil offset. If the borescope is moved more than 1.0 mil, then appropriate verification of the FCS bench-mark data must be performed.

The guidance rf beam is the reference for all of the rf beams. When checking beam zero indication (BZI) on a radar collimation shore tower, the borescope cross hairs, when centered on the proper target, should coincide with BZI.

### Guidance Beam Boresight

The guidance beam boresight is determined on the AN/SPM-9 in the CRO position by positioning the director in train and elevation to minimize the amplitude modulation appearing on the pulse, as shown in figure 8-20. The BZI on the radar test set occurs when the tower receiving horn is at the exact center of the guidance beam.

Borescope-to-target position is read from the director telescope cross hairs in milliradians. To

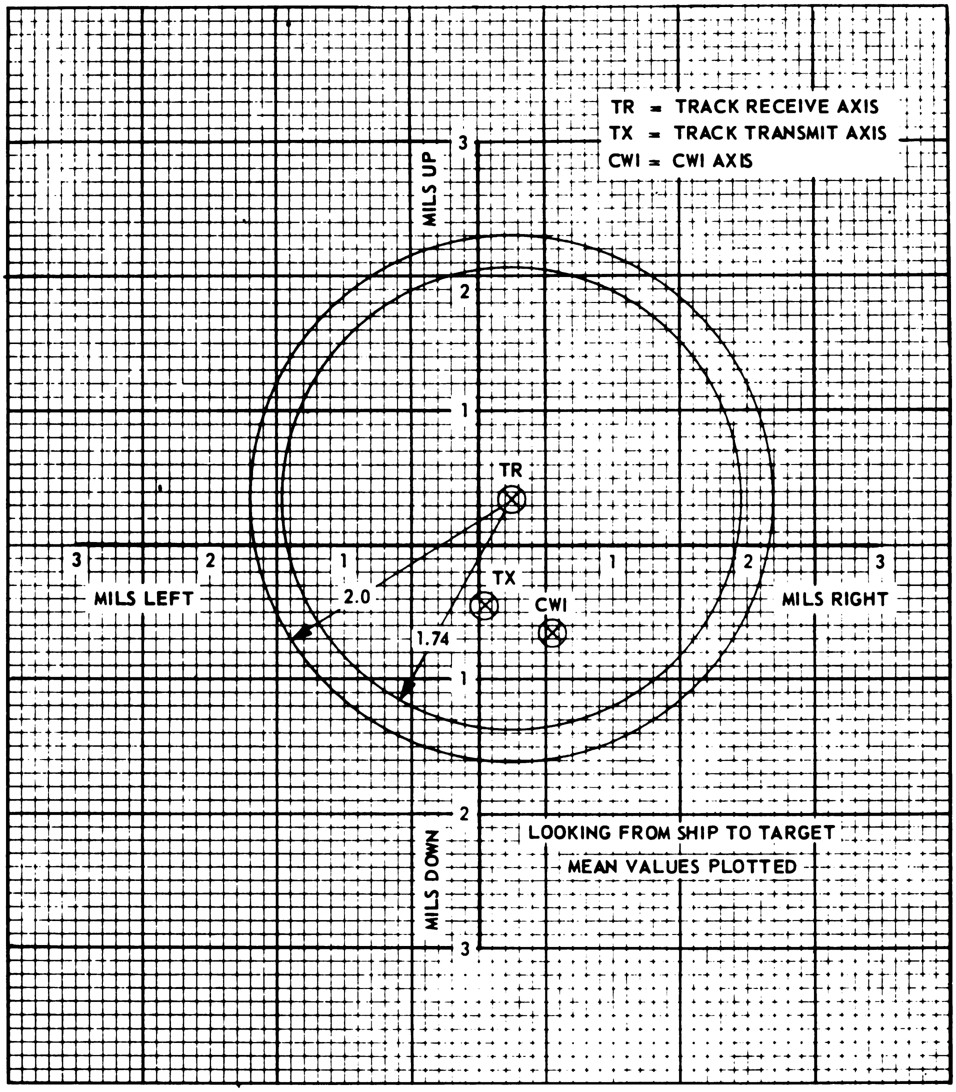

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Figure 8-19.—Beam position summary graph.

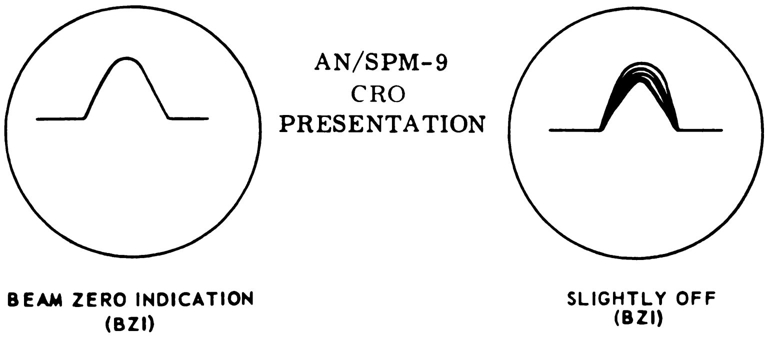

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Figure 8-20.—Guidance beam zero indication (BZI).

avoid confusion, you should log all borescope data with respect to the target; that is, 1.0 mil LEFT and 1.0 mil DOWN means that cross hairs on the borescope are 1.0 mil left of and 1.0 mil below the center of the target. Figure 8-21 shows the reticle pattern of the Mk 115 borescope.

The radial displacement of the borescope line of sight from the guidance beam center can be determined graphically by means of a graph similar to that previously shown in figure 8-19, or it can be calculated by finding the square root of the sum of the squared displacements in each axis. For example, if the borescope cross hairs are 0.2 mil above optical target center in the elevation axis and 0.4 mil right of optical target center in the traverse axis when guidance BZI is indicated on the test set, then the radial displacement between guidance beam center and the borescope line of sight is

$$E_R = \sqrt{\Delta T^2 + \Delta E^2} = \sqrt{0.2^2 + 0.4^2} = \sqrt{0.2} = 0.44 \text{ mil radial.}$$

The allowable borescope reading variance from nominal should not exceed 0.5 milliradians radially. The nominal value for shore tower collimation is 0.0 mil. For ship tower collimation, the nominal value is derived from previously

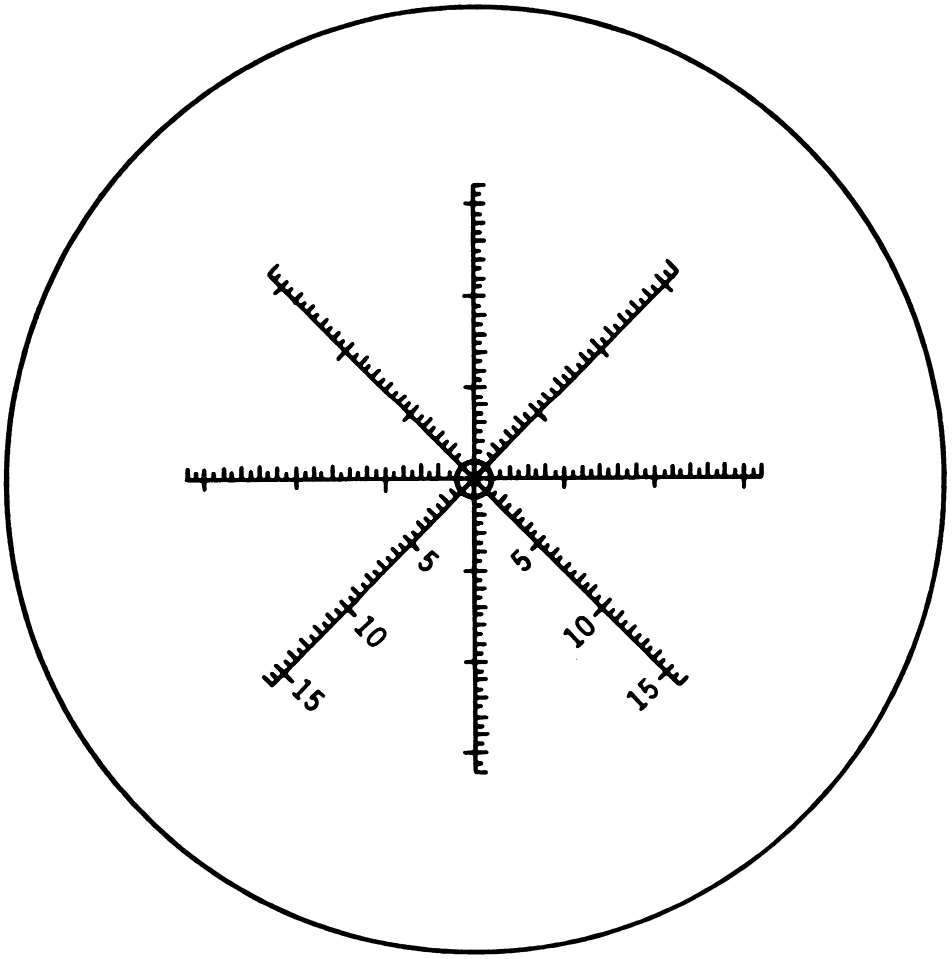

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Figure 8-21.—Telescope reticle pattern.

established shore tower collimation and ship correlation data.

### Capture Beam Boresight

The test setup aboard ship consists of placing the capture in RADIATE mode and hand cranking the director to the position previously determined to be associated with guidance BZI. The intent is to establish the capture radar beam boresight in alignment with the guidance radar beam boresight. The Radar Test Set AN/SPM-9 is connected to receive the capture rf by way of horn A on the tower. Capture beam boresight is determined on the radar test set in the PULSE AM mode by observing the amplitude envelope present on displayed pulse train of detected capture rf pulses.

The pulse AM presentation consists of a 60-Hz modulation envelope riding on the detected capture rf pulses when the tower receiving horn is near capture beam center. The modulation peaks vary with minor receiving antenna offsets from beam center in the train axis, and the valleys vary with minor offsets in the elevation axis. For large offsets from beam center, the modulation envelope degrades to a symmetrical 30 Hz. The capture beam center is located when a BZI is noted on the radar test set, as evidenced by each successive 60-Hz AM peak (and valley) being equal in amplitude with its preceding and following counterparts. See figure 8-22 for a pictorial representation.

The capture beam is aligned to the guidance beam electronically using the % MODULATION and PHASE CONTROLS located on the radar ferrite controller cabinet. The % MODULATION CONTROL moves the capture beam up and down, and the PHASE CONTROL moves the capture beam left and right. The BZI on the radar test set is observed when the PULSE AM presentation displays symmetrical video peaks (train) and valleys (elevation), as noted in figure 8-22.

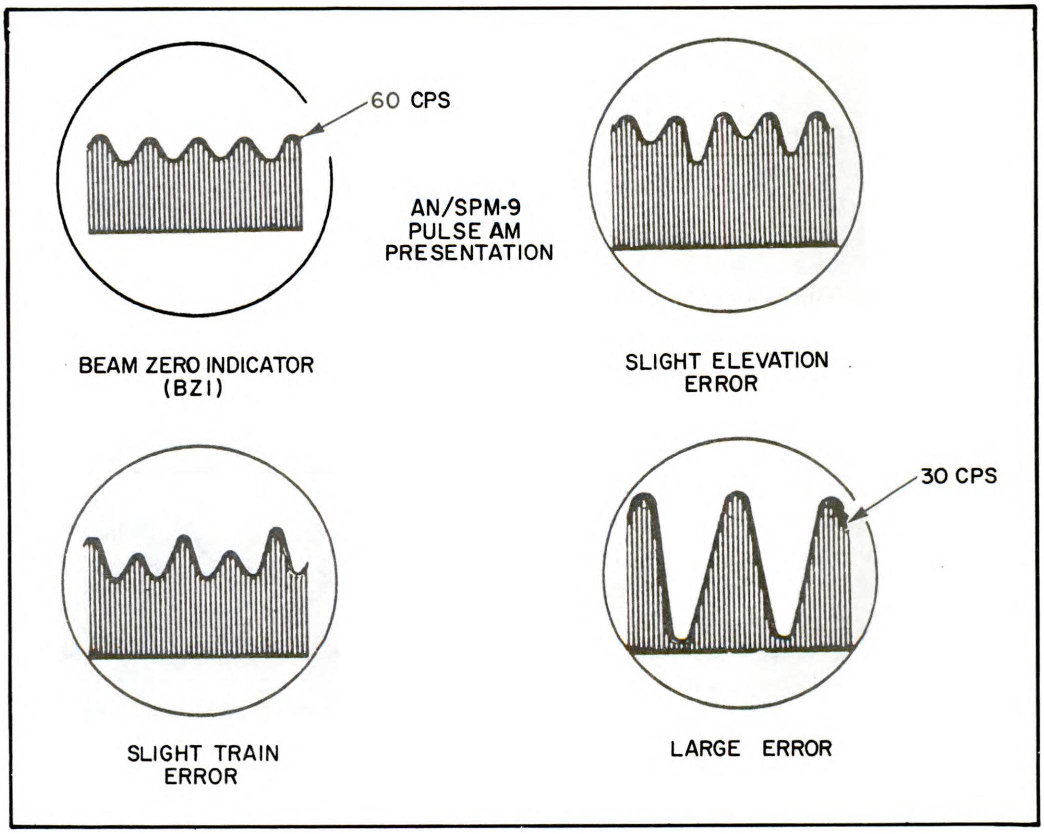

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Figure 8-22.—Pulse AM presentation.

### Capture and Guidance Beam Power Density

In these procedures, the Radar Test Set AN/SPM-9 is used as a microwave peak power indicator. The radar test set is connected to receive capture/guidance rf by way of horn A, and the director is hand cranked to the guidance boresight position. The procedure provides a measurement of beam power density. Typically, an external precision attenuator is used with the AN/SPM-9. The radar test set operator adjusts the precision attenuator until a stable 1-inch display of the detected third pulse is observed on the AN/SPM-9. The 1-inch deflection, with the SIGNAL ATTENUATION COARSE control at POWER SET and the SIGNAL ATTENUATION fine control at ZERO, is an indication of 1 milliwatt of peak rf power at the radar test set rf input terminal. This reading, when algebraically added to the patch cable losses, precision rf attenuation setting waveguide losses, and tower horn gain, establishes the rf power received at the tower.

### AM/FM Phasing

The capture and guidance are conically scanned in space at a 30-Hz rate, thus causing a receiving antenna displaced from beam center to see amplitude modulation (AM) on the rf. In addition, the transmitter PRF is frequency modulated (±5.5%) at the same 30-Hz rate. The radial distance of the missile from beam center is determined by the amount of AM on the received rf, while the direction of offset is determined by comparing the phase of the AM signal to that of the 30-Hz FM reference.

Beam phasing is determined on the radar test set in AM PHASE 2 position. In this position, a 30-Hz FM reference (derived from the received PRF) is applied to the vertical deflection plates, and the detected amplitude modulated carrier is placed on the horizontal deflection plates. A Lissajous pattern appears as a result of comparing the two signals. Radar phasing is measured by rotating the phase dial on the signal comparator until the Lissajous pattern closes with an UPRIGHT/DOWN LEFT slope, such as shown in figure 8-23. The radar phase is read directly from the phase dial. Phase error is determined by comparing the phase dial readings to the nominal phase readings when the director is offset in each axis by a standard amount.

### Capture and Guidance Modulation Slopes

Modulation slopes (angle sensitivity) are determined on Radar Test Set AN/SPM-9 in the CRO mode. The test set is connected to receive capture/guidance rf by way of horn A on the tower. The radar test set operator requests the director operators to establish BZI, and for capture, the operator requests a readout of train and elevation position from the radar console operator. From BZI, the director operators crank the director until the radar console operator for capture, or borescope operator for guidance, gives a mark for each director position required.

The amplitude modulation is measured by first establishing the position of the bottom of the modulated rf pulse (adjust radar test set SIGNAL ATTENUATION COARSE control for suitable presentation) at a convenient reference level on the display, and then by adjusting the external precision attenuator (increase attenuation until the peak modulation level drops to the previously established display reference level. The difference between the initial and final setting of the precision attenuator is the measured modulation slope value (in dB) for that director position offset from boresight. The measured modulation slope values are compared against nominal modulation slope values for specified director offset points from beam center to determine if the measured values are within tolerance. A pictorial representation of guidance modulation slopes is shown in figure 8-24.

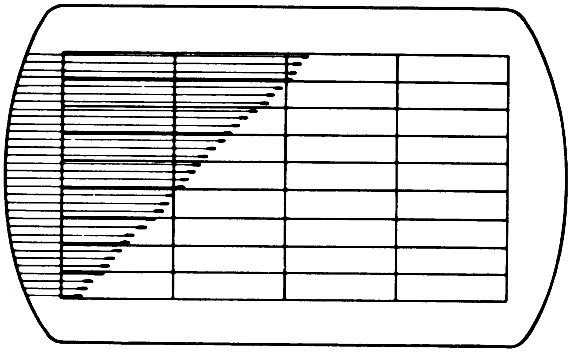

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Figure 8-23.—AN/SPM-9 AM phase 2 presentation (in phase).

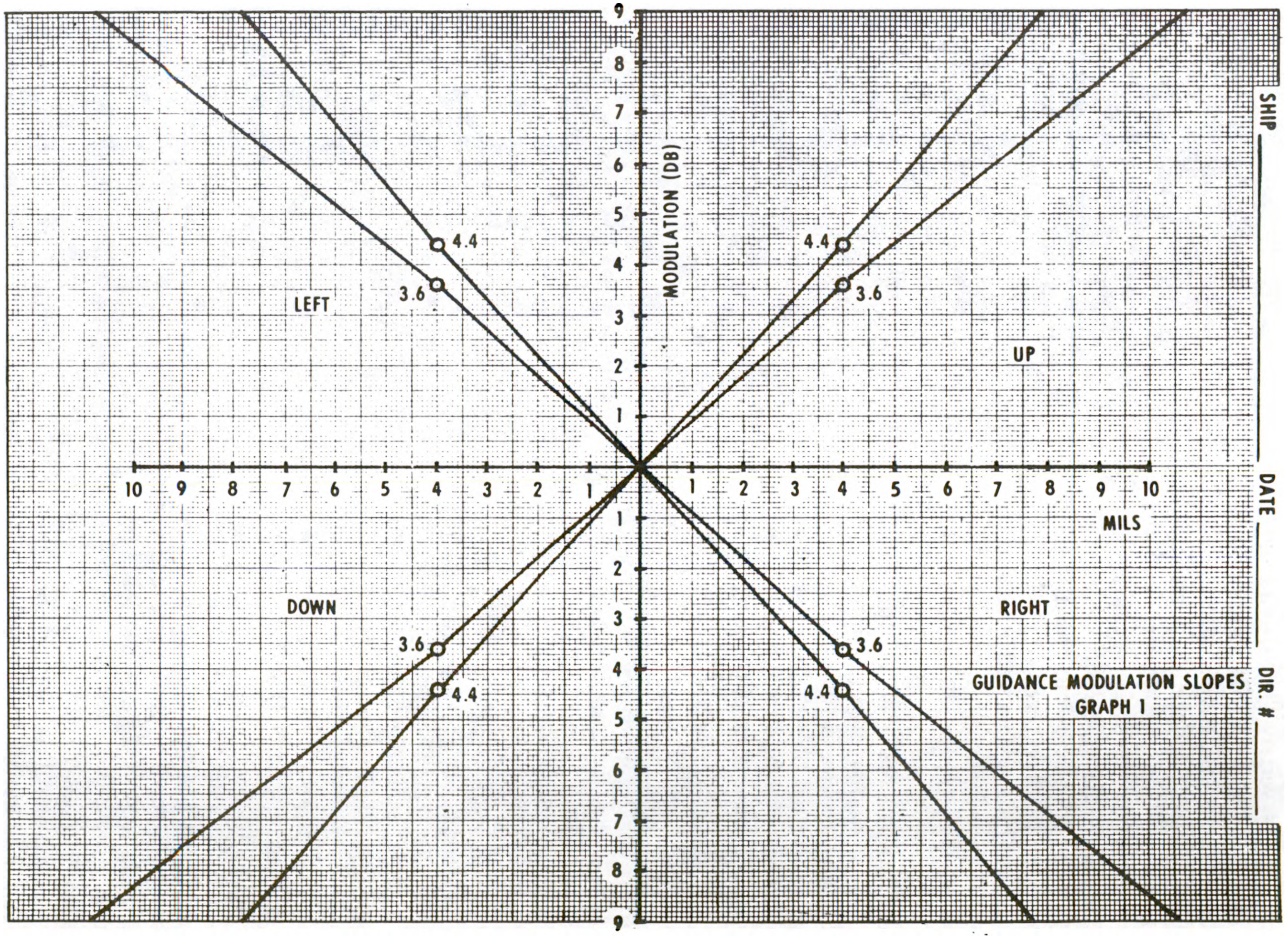

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Figure 8-24.—Guidance modulation slopes.

### Pulse Track Boresight

In these procedures, the Range Calibrator Set AN/UPM-115 is connected to receive and transmit track rf power by way of the tower guidance horn A. The director is hand cranked to a position near the guidance BZI.

The radar console operator acquires a simulated rf target from the tower, with the servo brakes set. When the target is acquired, the radar director operators reposition the director as necessary from guidance BZI to obtain 0 ±0.1 vdc from the pulse track receiver angle third detector error outputs (integrated). The radar telescope operator reads the new director position in milliradian displacement from guidance BZI in each axis.

The measurement is made in 1 PC (pulse compression), .1 PC, and narrow pulse modes, and the track-to-guidance axial displacement in each mode is then converted to radial displacement, either graphically or by finding the square root of the sum of the squared displacement in each axis. For example, if the measured track boresight in the 1 PC mode was found to be 0.2 mil DN and 0.05 mil RT of guidance BZI, then the radial track line of sight to guidance beam center displacement would be 0.21 milliradians.

$$E_R = \sqrt{\Delta T^2 + \Delta E^2} = \sqrt{0.05^2 + 0.2^2} = \sqrt{0.0425} = 0.21 \text{ mil radial.}$$

The maximum allowable track-to-guidance beam radial displacement in any pulse receiver mode is 0.25 mil.

### Pulse Track Angle Sensitivity

To perform this test, the radar director is initially positioned to track BZI and then repositioned UP 5 milliradians. The radar console operator places the radar in 1 PC mode and locks onto the AN/UPM-115 simulated target video radiated from the tower. The pulse track receivers are then adjusted to provide an elevation angle error signal of +6 ±0.3 vdc. This scales the receiver angle sensitivity to the desired 1.2 v/mil.

Following this, the director is repositioned DOWN 5 milliradians and the pulse track receivers should provide an elevation error output of −6 ±0.3 vdc. The procedure is repeated in the traverse axis.

Once the receiver's primary operation has been aligned and verified, the receive's secondary modes, .1 PC and narrow pulse, are tested.

### Doppler Track Boresight

As mentioned earlier, the CWAT tower transponder (fig. 8-14) is used during collimation to determine Doppler track boresight and to measure Doppler track angle sensitivity. The CWAT tower transponder is connected to receive through tower horn 0 and transmit through a precision X-band attenuator in series with tower horn B. The radar director is hand cranked to optical boresight on tower target one.

Upon receipt of the rf from the radar cwi transmitter, the CWAT tower transponder provides a Mach 3.8 inbound Doppler target. After the radar control operator acquires the target, the CWAT transponder operator then adjusts the target signal level with the precision attenuator until the radar console operator gives a mark when 4 ±0.4 vdc is measured from the doppler receiver log dc outputs. This establishes a 40-dB signal to noise ratio.

Once this is accomplished, the director is repositioned as necessary to obtain a Doppler receiver integrated elevation and traverse angle error of 0 ±0.2 vdc. The borescope cross hair to optical target displacement is then noted and compared against the previously recorded borescope to optical target displacement for guidance boresight in determining receiver line-of-sight displacement with respect to guidance beam center in both the TV and EL axis. The axial alignment errors are then converted to radial error by using the graphical method or by calculating the square root of the sum of the squared displacements in each axis. The radial Doppler-track line of sight to guidance-beam center displacement should not exceed 1 milliradian.

### Doppler Track Angle Sensitivity

This procedure is performed after the Doppler track boresight has been verified. The CWAT tower transponder is connected in the same manner as for performing Doppler track boresight.

The CWAT transponder produces a simulated Mach 3.8 target with a 40-dB signal-to-noise ratio to the Doppler radar. The radar director is initially positioned to Doppler track boresight, locked on to the target, and then sequentially offset 5 mils in each axis. At each offset point, the receiver output for the axis under test is checked and/or adjusted to produce 6.0 ±0.3 vdc of angle error, thus scaling the receiver angle error outputs at the desired 1.2 v/mil and ensuring proper symmetry.

## SUMMARY

This chapter has provided you with the basic principles of collimation using the most commonly employed fire control systems as examples. The actual collimation procedures for your system are contained in specific OPs or MRC cards.

In brief, collimation is the procedure whereby the rf axis(es) of a radar is/are brought into alignment (parallelism) with the mechanical axis of the radar. The mechanical axis is established by a telescope or boresight, while the rf axis is established by the rf beam of the radar.

The collimation shore tower provides the means of checking the parallelism between the rf axis and the optical (mechanical) axis. It contains optical targets for establishing the optical axis, and test antennas for establishing the rf axis. The test antennas and optical targets are mounted on a metal frame and spaced to correspond to the spacing between the center of the rf axis and the telescope or boresight axis of each shipboard radar. This eliminates parallax errors caused by the small ship-to-tower distance involved in normal tower operation.

In some radar systems, the optical axis is the reference axis and the rf beam is adjusted to it; while in other radar systems, the rf beam is the reference axis and the optical axis is adjusted to it. In addition to determining the collimation error between the rf axis and the optical axis, the power density of the rf beam and the angle error sensitivity of the radar is checked.

# CHAPTER 9

# MAINTENANCE

It is not uncommon for a second class petty officer to be in charge of a work center. You should keep this in mind when you study for advancement because you could find yourself in the position of a work center supervisor. As an FC2, you will need a broader knowledge of a variety of subjects to perform your duties in a professional manner. One area that you cannot take lightly is maintenance. Your fire control system is kept at its maximum level of readiness through maintenance.

As you advance, you will need to know more about testing equipment and systems and the interrelationships between your system and other elements of the combat system. The occupational standards for the FC rating list the minimum areas of expertise required. Many times you will have to take the initiative to acquire a working knowledge of support systems or a knowledge beyond the minimums covered by the occupational standards. In doing so, you are preparing yourself to handle any task assigned to your work center or division. This chapter presents many of the factors you will need to consider in the broad area of maintenance.

## PLANNED MAINTENANCE SYSTEM (PMS)

Combat system readiness requires efficient maintenance. The key to this capability is an organized system of planned maintenance that is designed to ensure the maximum operational readiness of the combat system. The OPNAVINST 4790.4A, *Ships' Maintenance and Material Management (3-M) Manual*, establishes an effective PMS and assigns PMS management responsibility.

The PMS provides regularly scheduled tests used in detecting degraded performance and aids in preventing failures (preventive maintenance) during tactical operations. When failures occur during combat system operations, PMS provides formal step-by-step fault isolation and repair procedures (corrective maintenance). Complete technical documentation, including combat system, subsystem, and individual equipment manuals, is an integral part of PMS. These manuals provide the necessary information for understanding, operating, and maintaining the combat system.

Shipboard maintenance falls into three categories: maintenance within the capability of ship personnel (organizational level); maintenance requiring assistance from outside the ship (intermediate level), such as tender or mobile technical unit; and maintenance requiring port facilities (depot level), such as shipyard maintenance. Since the objective of PMS is to perform maintenance on the organizational or intermediate level, depot-level maintenance is not reflected in PMS.

The PMS is a planning and control system that prescribes a logical and efficient approach to complex mechanical, electrical, and electronic maintenance. The PMS was developed to provide each maintenance-level supervisor with methods for effectively planning, scheduling, and controlling shipboard maintenance. The PMS includes a maintenance data collection system, which is used to record important scheduled and corrective maintenance information, and electronic data processing capabilities, which are used to retrieve this information for maintenance analysis.

## PMS OBJECTIVE

The PMS objective is to maximize operation efficiency of all equipment and to reduce down time, maintenance man-hours, and maintenance costs. Although PMS provides methods and resources to accomplish each objective, it is not self-sufficient and does not replace the initiative of maintenance supervisors nor reduce the necessity for technically competent personnel. Recording and providing feedback of maintenance and personnel data allows continuing management analysis for the improvement of maintenance methods and personnel management. Full use of the planning methods, along with the acceptance and cooperation of technicians, supervisors, and management personnel, produces a maintenance system with the inherent confidence, reliability, and capability to ensure the availability of the combat system.

Empirical data gathered from the fleet show conclusively that those ships that adhere to their PMS schedule maintain a significantly higher state of material readiness with no greater maintenance manpower usage than those ships that do not.

The primary ingredients of the PMS program are as follows:

- Comprehensive procedures for planned maintenance of the combat system, subsystems, and equipment
- System fault isolation procedures
- Scheduling and control of maintenance task performance
- Description of the methods, materials, tools, and personnel required for maintenance

Adherence to the PMS program will produce the following results:

- Improved confidence in system maintenance
- Reduced testing time
- Elimination of redundant testing resulting from uncoordinated testing
- Detection of most malfunctions during scheduled maintenance events

## MAINTENANCE SCHEDULING

The normal flow of events the maintenance managers use in developing an integrated maintenance schedule is shown in figure 9-1. This figure shows maintenance management responsibilities and the sequence of events that flow from the departmental master and work center PMS record books through the scheduling aids (cycle, quarterly, and weekly schedules) to test execution, unscheduled maintenance, and reporting.

### Maintenance Index Pages (MIPs)

The MIPs contain a brief description of the requirements on the maintenance requirements card for each item of equipment, including the periodicity code, the man-hours involved, the minimum required skill level, and, if applicable, the related maintenance requirements. The MIPs for all equipment in a department are contained in the department's master PMS record. The department's master PMS record is used by the department head to schedule maintenance on the PMS schedule forms. Each work center has a work center PMS record that contains the MIPs that are applicable to that work center.

### Cycle Schedule

The cycle schedule is a visual display of preventive maintenance requirements based on the ship's current overhaul cycle. It is used by department heads to assist in quarterly planning of non-PMS related activities (inspections, training, and so forth).

### Quarterly Schedule

The quarterly schedule, planned from the cycle schedule, is a visual display of the ship's employment schedule. This schedule is prepared by department heads in cooperation with division officers and maintenance group supervisors. The schedule shows the current status of preventive maintenance for each group and assigns specific requirements in conjunction with the ship's operational schedule.

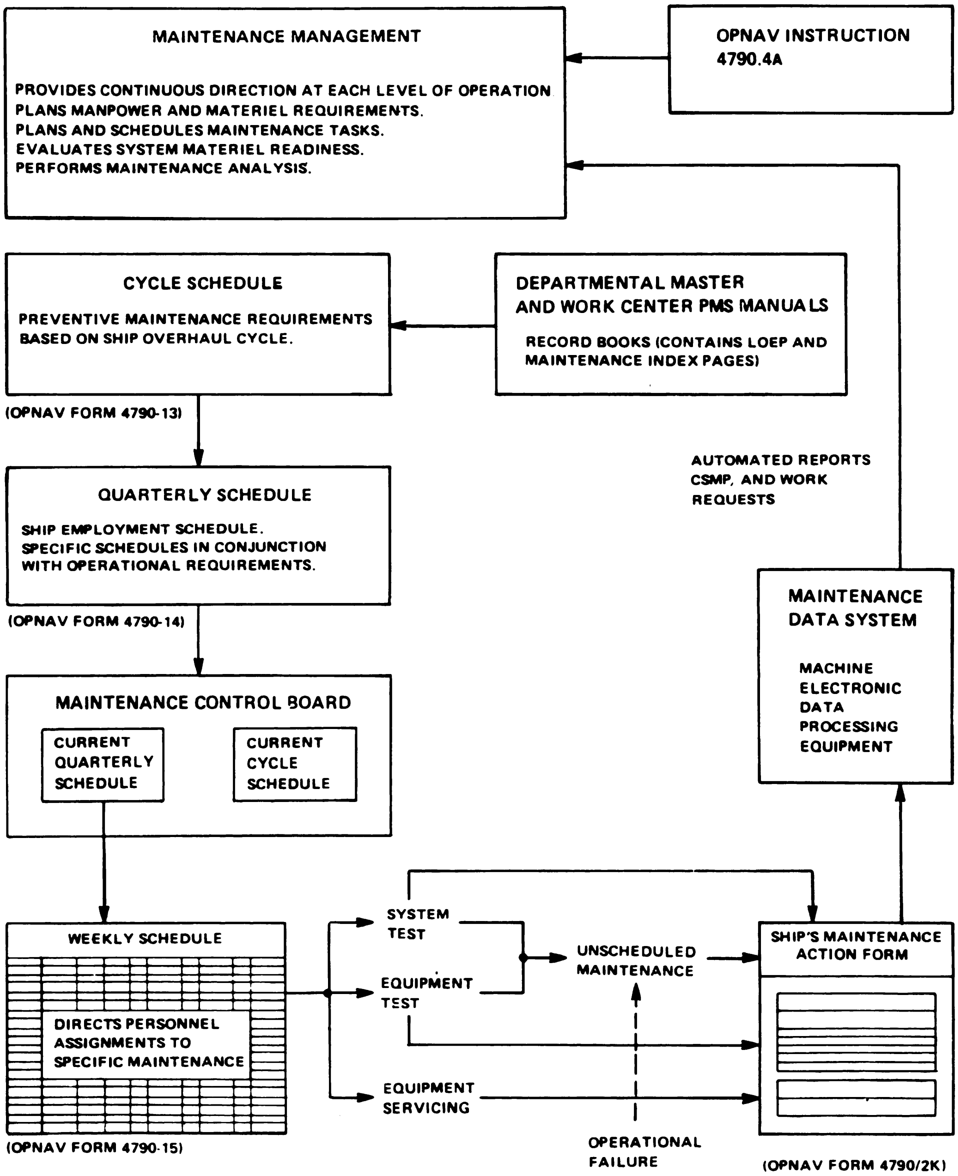
MAINTENANCE MANAGEMENT
PROVIDES CONTINUOUS DIRECTION AT EACH LEVEL OF OPERATION
PLANS MANPOWER AND MATERIEL REQUIREMENTS.
PLANS AND SCHEDULES MAINTENANCE TASKS.
EVALUATES SYSTEM MATERIEL READINESS.
PERFORMS MAINTENANCE ANALYSIS.
OPNAV INSTRUCTION 4790.4A
CYCLE SCHEDULE
PREVENTIVE MAINTENANCE REQUIREMENTS BASED ON SHIP OVERHAUL CYCLE.
DEPARTMENTAL MASTER AND WORK CENTER PMS MANUALS
RECORD BOOKS (CONTAINS LOEP AND MAINTENANCE INDEX PAGES)
(OPNAV FORM 4790-13)
AUTOMATED REPORTS CSMP, AND WORK REQUESTS
QUARTERLY SCHEDULE
SHIP EMPLOYMENT SCHEDULE.
SPECIFIC SCHEDULES IN CONJUNCTION WITH OPERATIONAL REQUIREMENTS.
(OPNAV FORM 4790-14)
MAINTENANCE DATA SYSTEM
MACHINE ELECTRONIC DATA PROCESSING EQUIPMENT
MAINTENANCE CONTROL BOARD
CURRENT QUARTERLY SCHEDULE
CURRENT CYCLE SCHEDULE
WEEKLY SCHEDULE
DIRECTS PERSONNEL ASSIGNMENTS TO SPECIFIC MAINTENANCE
(OPNAV FORM 4790-15)
SYSTEM TEST
EQUIPMENT TEST
UNSCHEDULED MAINTENANCE
EQUIPMENT SERVICING
OPERATIONAL FAILURE
SHIP'S MAINTENANCE ACTION FORM
(OPNAV FORM 4790/2K)

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Figure 9-1.—Planned maintenance system, block diagram.

## Maintenance Control Board

The maintenance control board contains the cycle schedule and the current and subsequent quarterly schedules. The board summarizes the status of current and planned combat system preventive maintenance. It is updated on a weekly basis by the division officer for all deferred and completed maintenance items.

## Weekly Schedule

The weekly schedule is a visual display that is posted in the working area of each maintenance group. The maintenance group supervisor uses the weekly schedule to assign specific personnel to perform maintenance on specific equipment. Assignments include system and equipment tests and servicing procedures.

## MAINTENANCE DATA SYSTEM

The maintenance data system (MDS) provides a means of recording maintenance actions, processing the recorded data to define important facts about maintenance and equipment, and retrieving information for analysis. Significant data identified by the system include the reason the malfunction occurred, the manner in which it was discovered, man-hours expended, exact equipment affected, delays in repair, reasons for delays, and types of maintenance personnel required.

### Recording

Maintenance personnel should document certain shipboard maintenance actions and corrective maintenance on specific categories of equipment at the time maintenance actions were performed or deferred. Information is recorded and submitted to the MDS for input using OPNAV Form 4790-2K, Ship's Maintenance Action.

### Data Processing

The MDS data processing facilities collect, store, and analyze maintenance information inputs into the system. The MDS yields a data path concerning equipment maintainability and reliability, man-hour usage, equipment alteration status, material usage and costs, and the fleet material condition. Various automated reports are produced periodically for the ship, repair activities, unit commanders, and type commanders. These automated reports include current ship's maintenance project files, work requests, and preinspection and survey deficiency listings.

## INTEGRATED MAINTENANCE

Combat system maintenance is based on a concept of performing a comprehensive schedule of tests at three mutually supporting levels: combat system, subsystem, and equipment. These integrated tests are structured to challenge all combat system functions, parameters, and characteristics on a scheduled periodicity against specified tolerances. Successful performance of the test as scheduled should provide a high level of confidence in the functional operability of the combat system equipment.

Integrated maintenance requirements are established through engineering analysis based on the study of all factors having a significant effect on maintenance. The analysis defines system and equipment functions and establishes tolerances in terms of system parameters that allow a means of determining acceptable system operations.

The integrated maintenance procedures are intended to provide minimum preventive maintenance coverage of the combat system. The procedures are written to establish specific controlled conditions that challenge the functions under test. In some cases, test efficiency and format restrictions make it difficult to determine the intent of a test from its procedural steps; therefore, it is mandatory that procedural sequences are followed explicitly. Improvising or shortcutting procedural sequences often leads to incorrect troubleshooting or masking of actual faults.

The integrated maintenance concept is consistent with the PMS efforts, and it is the most effective means of achieving the goals of PMS. Adhering to this concept enables maintenance managers to manage the combat system maintenance effort and achieve an optimum level of readiness with the most effective use of available personnel.

A block diagram summary of the integrated maintenance concept is shown in figure 9-2, a foldout at the end of this chapter. The upper level shows the scheduled maintenance test entry into system maintenance. The second level shows the possibility of operational entry. The third level shows the combat system, subsystem, and equipment fault isolation process; the fourth level shows corrective maintenance, verification, and reporting.

With combat system testing being conducted at three levels (combat system, subsystem, and equipment), it is imperative to integrated maintenance that tests are scheduled to reduce test redundancy whenever possible. The three levels of tests are described in the following paragraphs.

### Combat System Testing

Combat system testing, defined as testing that exercises the combat system as one entity, is the highest level of testing that can be accomplished aboard ship. Combat system tests are usually automated and are conducted and monitored from the ship's command and control center (CIC, NTDS, DDG-TDS, and so forth).

The overall combat system operability test (OCSOT) is the primary combat system test tool. The OCSOT gives a good overview of detection, display and tracking, designation, acquisition, repeat back position, and some status signal monitoring. Simulated targets are used in the OCSOT. Although the test is conducted as if the combat system were operating normally, certain operating stations dedicated to support the test are lost for normal operational use.

While the OCSOT provides an overview of system performance, it does not test the full capacity of the combat system or its subsystem operability. It is impractical from an instrumentation and manpower standpoint to test all functional test requirements for the combat system level. Therefore, confidence in operability or material readiness is mainly dependent on integrated testing at the subsystem and equipment level.

### Subsystem Testing

Testing that exercises two or more pieces of equipment functionally contained within the same subsystem is defined as subsystem testing. The intent of subsystem testing is to test a subsystem in stand-alone operation; however, some functions are provided by other subsystems, which require integrated testing.

Subsystem tests are functionally grouped and mode oriented so that related functions may be challenged using the same setup, procedures, and stimuli. Where practical, subsystem tests use tactical indicators for measurement, leaving the requirement for special hookups and test equipment to equipment-level testing.

A major combat ship contains most or all of the following subsystems:

- Search radar subsystem
- Command and control subsystem
- Countermeasure subsystem
- Gun weapon subsystem
- Guided missile weapon subsystem
- External communication subsystem
- Navigation subsystem

An example of the relationship of combat system components is shown in figure 9-3.

### Equipment-Level Testing

Equipment-level testing is generally directed toward power levels, frequencies, servos, special features, and output functions. The equipment PMS may require special external stimulating equipment and special- or general-purpose test equipment for test measurements. These levels of testing are discussed later in this chapter.

## FAULT ISOLATION

To diagnose and effect timely repair of faults within your fire control system, you must have a knowledge of fault isolation concepts, the fault isolation tools available to you, and the capabilities and limitations of these tools when applied to system fault isolation. The objective of fault isolation is the systematic application of fault isolation tools needed to isolate the exact unit or functional interface responsible for a fault or degraded operation during testing or tactical operation.

Although the primary entry into fault isolation is from test-detected faults, improper operating conditions can be observed during tactical operations, including operator awareness, data extraction and reduction, and on-line monitoring.

After a fault has been isolated to a specific unit or interface, corrective action in the form of repair, replacement, or alignment must be taken.

Fault isolation leads to corrective maintenance. The corrective maintenance performed may or may not be required to bring the system back to an operable condition. There may have been more than one fault contributing to the out-of-tolerance condition that initiated the fault isolation process. The possibility of faulty replacement parts and incorrect adjustment or alignment exists. Corrective maintenance may not have solved the problem, or it may have added

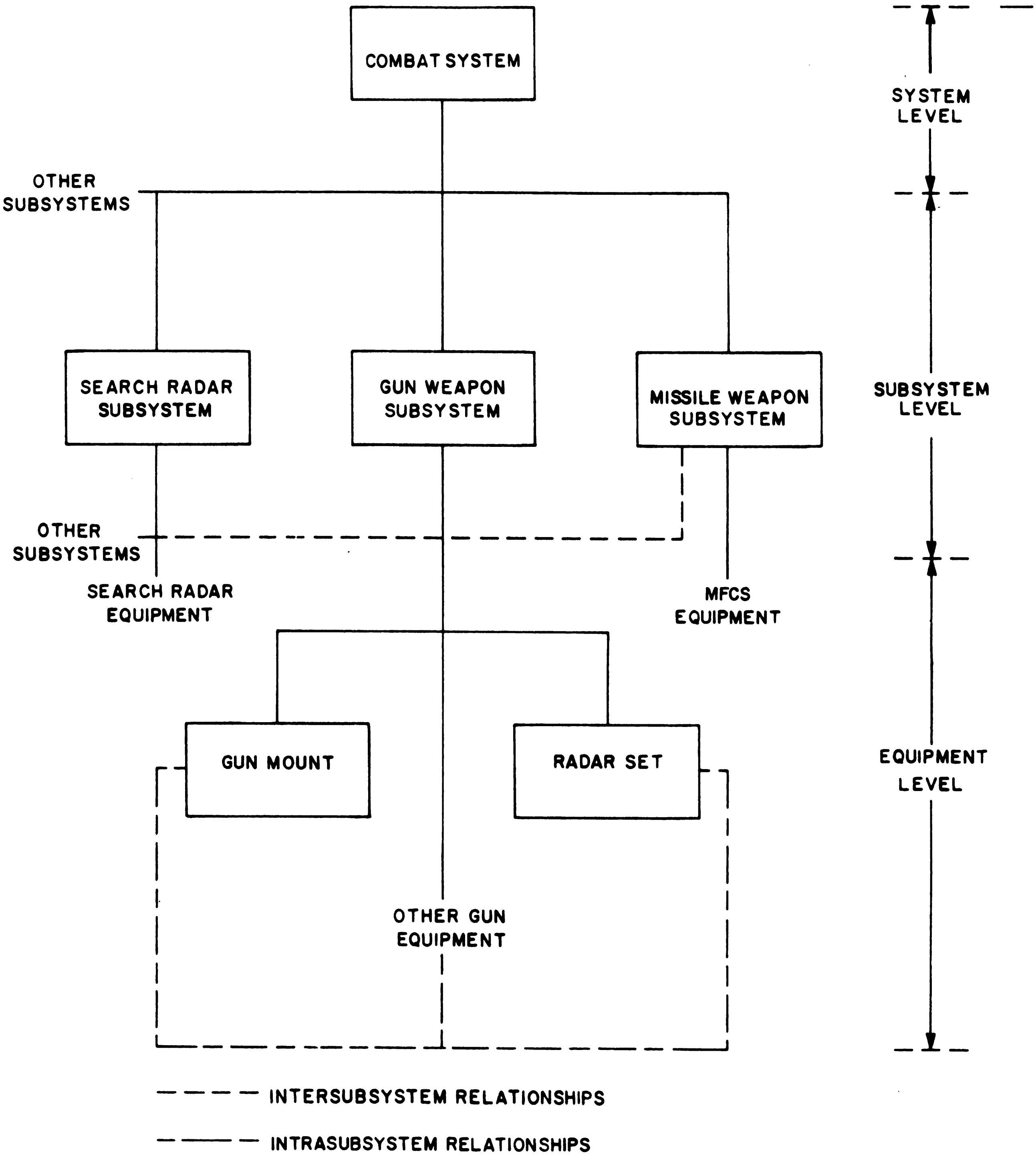

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Figure 9-3.—Combat system relationships.

to it. Therefore, it is mandatory that each corrective action be followed by verification. Normally, verification is accomplished by recreating the test environment and rechallenging the function. Where alignments are concerned, the interdependent effect upon other elements of the combat system has to be considered in the verification process.

## FAULT ISOLATION TOOLS

During testing or operational use of a weapon system, faults can occur in the interface between subsystems, in the interface between equipments of a subsystem, and in the equipment itself. Rapid fault isolation requires decisive action in selecting and implementing the most appropriate fault isolation tools. A fault isolation tool has the following characteristics:

- Requires the least amount of time, equipment, or service
- Is easily implemented
- Conveys the maximum intelligence regarding the source of the fault

Tools employed in fault isolation cover a wide range of applications, which includes (but is not limited to) the following: combat system test, subsystem tests, on-line testing, off-line testing, diagnostic testing programs, and maintenance support documentation. In the following paragraphs, we will cover some of these items and give examples of their use, where appropriate.

### Combat System Tests

As stated earlier, combat system tests are the highest level of tests that can be performed to verify combat system readiness or alignment. The OCSOT is one of the major combat system tests; it is designed to test the combat system as a single, functional unit. Major faults in the subsystems usually show up during the OCSOT. Often, this is the first indication of a problem in a particular subsystem. For example, if the guided missile fire control system (GMFCS) computer is experiencing a hardware problem that affects input data, during the section of the OCSOT where intersystem designation is attempted from the gun fire control system (GFCS) to the GMFCS, the GMFCS is unlikely to lock on to the target from the GFCS because of erroneous data. In this situation, another combat system test might be attempted. One such test is a GFCS/GMFCS Intersystem Designation Test (CS-XX/W-XX). This test verifies the accuracy of the transmission of target position data between the gun fire control system and the missile fire control system. Major components of each system are exercised during the test and a hard-copy printout of fire control parameters (range, bearing, elevation, and so forth) can be obtained from the computer printer.

Another important test is the Combat System Alignment Test (CS-XX/R-XX). The combat system alignment test is a programmed test tool designed to measure the relative beam alignment (or misalignment) between a reference sensor and a sensor under test. The measure of misalignment is accomplished by collecting the range, bearing, and elevation data from the reference and test sensors; then comparing the test sensor data to the reference data and displaying the results on a display console for analysis. A hard-copy printout can be obtained to provide a record. The sensors that can be tested include the gun or missile fire control radars and surface or air search radars.

### Subsystem Tests

Subsystem tests aid in fault isolation by testing specific functions within a subsystem to determine if they are generated correctly. In many cases, these tests check the transmission of data between the subsystem under test and associated subsystems. Computer programs are available that provide specific test capabilities suited to subsystem testing. An example of such a program is the programmed operational functional appraisals (POFA). The POFA programs, for which the subsystem test is named, are nonresident programs that detect and isolate malfunctions by transmitting selectively configured and controlled data between computer and computer ancillary equipment interface.

A typical example of a subsystem test is the GMFCS daily system operability test (DSOT). The purpose of the DSOT is to assess weapon system readiness in the normal mode of operation for an antiaircraft (AA) target from *designation* through *acquisition, track, weapon control, simulated firing*, and *postfiring evaluation*.

Test procedures are controlled by the test conductor. The test conductor calls out the step numbers in sequence; the personnel performing the steps in the various spaces inform the test conductor when the action or observation required by that step is completed. No response restrictions are placed on personnel except where the steps are underlined in the procedure. In this case, instruction words are also underlined indicating the quantity or indication upon which the request for the response is based. Steps not underlined, but containing underlined instructions, denote the response requested; for example, *Mark*, *Fired*, and so forth. Underlined step numbers denote those steps to be recorded for evaluation and scoring. All responses should be given as soon as practical after the completion of the step, particularly in those areas of the test where the timing is important or when a sequence of events must commence immediately after a required action or observation. Timely responses aid in decreasing time requirements.

Before initiating detailed fault isolation procedures when a fault occurs during combat system or subsystem testing, the operational step (or steps) should be repeated to ensure the fault is an actual fault and not an operator error. Should the fault still exist, you should ensure the combat system or subsystem is properly configured for the test event performed; that is, switches are properly set, correct function codes are selected, and so forth.

### On-line/Off-line Testing

Based on the level of testing selected, on-line maintenance testing can assist in fault isolation by testing suspected equipment or systems with a minimum of interference with normal ship operation. If a suspected equipment or system checks out satisfactorily, then a possible source of the fault has been eliminated. This aids in the fault isolation process. In general, the use of on-line testing provides a quick fault isolation tool when trying to confirm equipment/system problems. When using on-line testing, you should be careful not to degrade the system/subsystem operational capability beyond the level specified by ship doctrine.

Some combat system equipment has the capability of severing normal communication links and accepting preset or manual inputs when verifying system ability to correctly process data. This is referred to as off-line testing, and it offers a convenient method of isolating equipment or interface faults. As in on-line testing, care must be taken not to degrade the system/subsystem operational capabilities. One such off-line test is the system maintenance test (SMP) used in the Mk 86 GFCS.

The system maintenance program (SMP) is a computer program that enhances functional testing and troubleshooting of the FCS. It is loaded into the FCS computer in place of the normal (tactical) FCS operational program. Therefore, the FCS is not functional in a tactical sense until the FCS operational computer program has been reloaded into the FCS computer following utilization of the system maintenance program. The purpose of the SMP is to provide test conditions to check the integrity of input/output circuits to and from the computer and to check the functional integrity of various functional systems (fig. 9-4).

The program includes a configuration entry routine, an executive routine, and approximately 60 individual tests that are organized into groups according to the interface channels between the computer and peripheral units. Configuration entry allows the technician to adapt the program to a particular modification of the fire control system. The executive routine provides the basic timing requirements for each test program and establishes testing priority in the event two or more tests are selected concurrently.

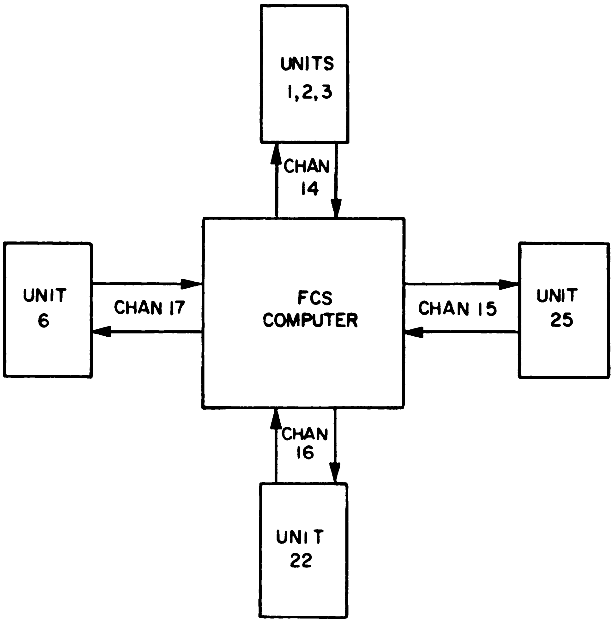

Figure 9-4.—System maintenance program/FCS unit testing relationship.

The tests are grouped according to the channel and unit numbers as follows:

Channel 14 test programs are selected from units 1, 2, and 3.

Channel 15 test programs are selected from unit 25.

Channel 16 test programs are selected from unit 22.

Channel 17 test programs are selected from unit 6.

A sample of channel 14 test programs is shown in table 9-1.

**Table 9-1.—System Maintenance Program Channel 14 Tests**

| CHANNEL 14 TEST PROGRAMS | |
|---|---|
| Unit 2, 3 Test Number Select Code | Test Selected |
| 00000 | Initial data display |
| 00001 | Address decode test |
| 00002 | Nixie cycle test |
| 00003 | WCC keyboard test |
| 00007 | Mode sequence indicators test |
| 00009 | WCC projectors test |
| 00010 | Inputs test 10 |
| 00011 | Inputs test 11 |
| 00020 | RAM test |
| 00021 | Symbol decoder test |
| 00022 | Screen test |
| 00040 | B-scan test - standard |
| 00041 | - reduced |
| 00042 | - X standard |
| 00043 | - X reduced |
| 00044 | - Y standard |
| 00045 | - Y reduced |
| 00050 | Gun data test |
| 00060 | Servo test - (gain = 16) |
| 00061 | - (gain = 8) |
| 00062 | - (gain = 4) |
| 00070 | Encoder test |
| 00080 | Gun align display |
| 00180 | Memory call up test - random |
| 00181 | Memory call up test - consecutive |
| Unit 1 Designator Select Switch | Test Selected |
| ROS | COC select 1 and 2 input words |
| NTDS | COC TDS input words |
| TARTAR | COC select 2 and COC/CWI or WCS input words |
| SPA | COC control input words |
| TDT1 | SRM trackball |
| TDT2 | PPI test |
| TDT3 | PPI (X) test |
| TDT4 | PPI (Y) test |
| SPQ9 | Marker test |
| SEARCH | B-scan range gate test |
| IDD | PPI range gate test |

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Notice that the tests selected at unit 2 or 3 are selected with a test number select code. The procedures for setting up these codes are as follows:

Step 1. At the matrix selector (group of six switches) on unit 2 or 3, press the TEST push button to light the legend green. This causes the test matrix (fig. 9-5) to appear.

Step 2. Press the TEST NO SEL push button (located on the first column of the first row of the matrix) to light its legend green.

Step 3. At the keyboard, press CLEAR, type in the test number select code, and press ENTER. The selected test will begin running. It is not necessary to type in leading zeroes. For example, if the test code is given as 00011, it is only necessary to type in 11.

Step 4. To terminate the test, press CLEAR and ENTER. This effectively enters test select code 00000, which terminates the test and calls back the initial data display.

It is not practicable to list all the possible tests in the SMP. The discussion that follows is limited to channel 14 test programs.

The channel 14 test programs consist of a scan generator test routine and various test routines that can be selected from unit 1, 2, or 3. Test routines are selected from unit 2 or 3 using test number select keyboard code entries to the computer. The DESIGNATOR SELECT switch positions at unit 1 select tests from unit 1. Table 9-1 lists units 2 and 3 test number select codes and unit 1 DESIGNATOR SELECT switch positions used to select the test routines. The following paragraphs provide a synopsis of selected channel 14 test programs.

INITIAL DATA DISPLAY. This routine provides an initial data display to the A/N display for entering initial test data required for the channel 17 end-around, D/A converter, gun data, and encoder tests.

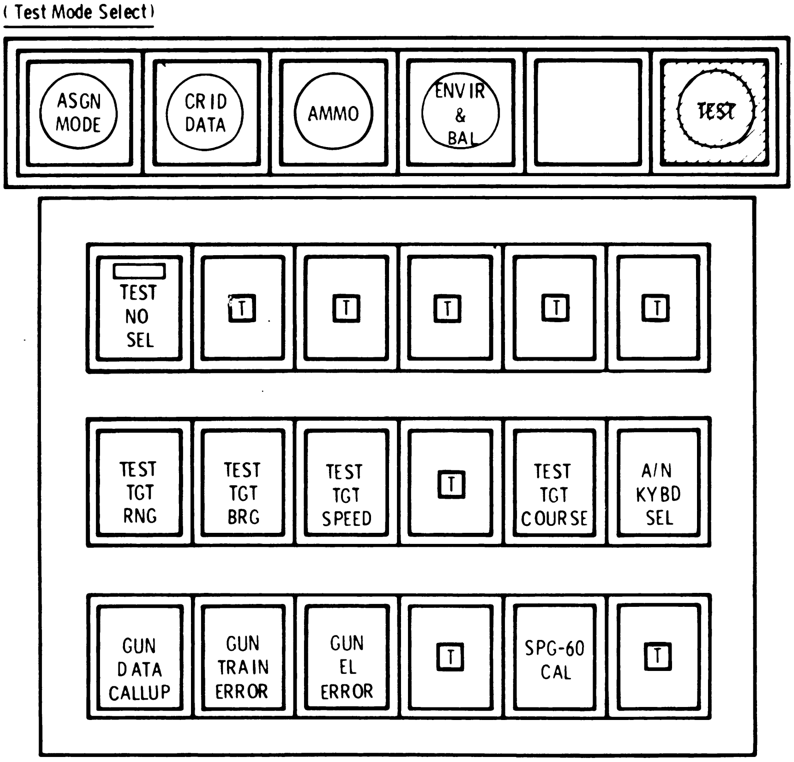

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Figure 9-5.—Sample test mode matrix.

ADDRESS DECODE TEST. This test routine outputs a unique number to each unit (1, 2, and 3) readout to verify proper address encoding and console address decoding.

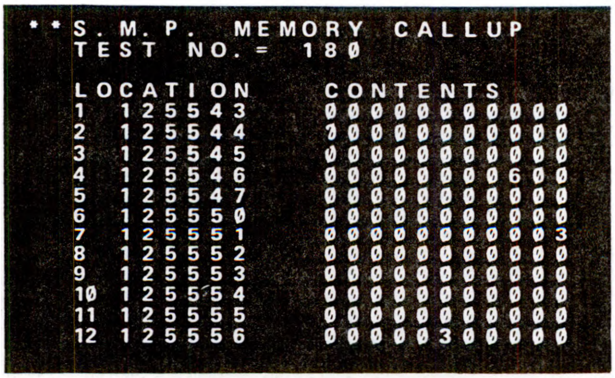
NIXIE CYCLE TEST. This test routine cycles all of the unit 1, 2, and 3 nixie readout digits from 0 to 9, in unison, in a 10-second period. The test checks the channel 14 output lines and the readout digital logic.

GUN DATA TEST. This test is similar to the channel 17 end-around test, except that the test results are displayed on the A/N display rather than on a typewriter printout. The test should be used for fault localization rather than fault detection.

SERVO TESTS. These tests check out the stiff stick data, camera assign codes, and the TV sight 1 and sight 2 servo systems. The servo systems can be checked using a servo gain of 8, 4, or 2.

MEMORY CALL-UP TESTS. The memory call-up tests are used to monitor up to 12 randomly selected or consecutive computer memory locations and to display them on the A/N displays.

When troubleshooting with the aid of the system maintenance program, it is sometimes useful to know what data the computer is transmitting and receiving. The memory locations of all active computer input and output buffers can be called up using this routine. An illustration of memory call-up is shown in figure 9-6.



```
**S.M.P.  MEMORY  CALLUP
  TEST  NO. =  180

  LOCATION      CONTENTS
  1   125543    00000000000
  2   125544    00000000000
  3   125545    00000000000
  4   125546    00000000600
  5   125547    00000000000
  6   125550    00000000000
  7   125551    00000000003
  8   125552    00000000000
  9   125553    00000000000
  10  125554    00000000000
  11  125555    00000000000
  12  125556    00000300000
```

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**Figure 9-6.—Sample display for memory call-up test no. 180 or 181.**

**Diagnostic Testing Programs**

Diagnostic testing programs are useful in locating a problem in a piece of equipment once the problem is isolated to a unit. The unit can be systematically tested with a printout or readout provided to the technician to indicate the problem area. Some diagnostic programs provide an error code readout, while others provide the direct location of suspected faulty components. An error code readout requires searching an area code table to locate the possible bad component, while the direct component location readout tells the technician where the problem could be located. The direct component readout method is usually faster in producing the location of suspected failed components.

Diagnostic programs are designed to isolate malfunctions that occur in the internal logic of the printed circuit boards. When other types of failures occur, manual procedures are required, but, in many cases, the diagnostics provide sufficient information to identify the functional area of the failure. The following paragraphs describe diagnostic testing of the Mk 152 computer.

The diagnostic testing sequence is initiated by performing a preload initialization procedure. In this procedure certain manual operations are performed to ensure that the equipment involved in the testing is in an initialized state before any testing is performed under program control. The initialization procedure ensures that the computer under test can be properly energized and initialized. If the preload checkout is successful, diagnostic program loading is attempted; if the preload checkout is unsuccessful, isolation is performed on the failure symptom noted during the attempted initialization. If isolation is unsuccessful, then diagnostic loading should be attempted.

In the initial load attempt, the input/output console is used to load the diagnostic program into memory with the normal bootstrap method. If the program is successfully loaded, it is then executed. If the bootstrap load attempt is unsuccessful, isolation is then performed using the failure symptom obtained from the unsuccessful load attempt. If the symptom results in a suspect card list of more than 10 cards, the operator has the option of replacing the suspect card or, if the other computer is available (in a dual-computer system), performing intercomputer loading of the diagnostic program.

Once the diagnostic program is loaded, it is then executed according to the appropriate program execution procedure to verify the operational status of the computer. If the program run is successful, indicating no detected malfunctions, the computer comes to a programmed stop, which indicates that the program ran successfully. If the program detects a malfunction, the computer either comes to an error stop, program faults, halts, or hangs up in a loop condition with the failure symptom displayed on the maintenance panel.

To isolate the malfunction, the technician correlates the failure symptoms displayed on the maintenance panel to the appropriate diagnostic tables, which lists the possible faulty components for the given failure symptoms.

### Maintenance Support Documentation

Maintenance support documentation falls into two general categories: (1) logic diagrams that contain a sequence of steps to isolate the faults causing a specific test- or operation-related fault symptom; and (2) system or equipment functional flow diagrams that allow the technician to determine a sequence of isolation steps. Logic diagrams include troubleshooting logic charts (TLC), fault logic diagrams (FLD), fault isolation pyramid charts, and fault reference tables. The TLCs and FLDs provide a simple yes or no question-and-answer approach to fault isolation. They are generally based on either a ladder method or a bracket-and-halving fault isolation technique. In the ladder method, the function is approached from its initiation or termination point and, in successive steps, is checked to the other end. In the bracket-and-halving fault isolation technique, the function is checked at its midpoint, then at the midpoint of the half containing the fault, and so forth, until it is isolated. Pyramid charts take an output or terminal function (output, indicator, and so forth) and break it down into its major subfunctions, which are individually checked until the fault is isolated. Fault reference charts generally relate symptoms to specific faults. Functional diagrams include system functional diagrams, signal-flow diagrams, schematic diagrams, and relay-ladder diagrams. These are frequently used in isolating a fault that was not anticipated by the fault logic material provided.

In general, fault logic procedures are used more rapidly (by inexperienced technicians) than functional diagrams in isolating a specific fault. When used with flow diagrams, fault logic procedures provide a means of teaching new or inexperienced personnel effective fault isolation techniques. A functional understanding gained through the use of maintenance documents is necessary for the development of experienced technicians. Experienced technicians frequently isolate specific faults addressed in fault logic procedures faster without referring to procedures. Their experience is essential in isolating problems that have not been anticipated by logic procedures.

Numerous approaches are possible in the application of fault isolation procedures. The fact that most casualties occur within an equipment and are corrected by troubleshooting on an equipment level leads to the tendency to troubleshoot all casualties on an equipment basis. It is to be expected that each technician might rely more heavily on certain troubleshooting aids and procedures than others. Few hard and fast rules are applicable to all troubleshooting situations, but one rule that should always be foremost is to determine the origin of a fault as precisely as possible.

System interrelationship is such that many casualties can be reflected in several areas as improper operation or fault indications. If each area of each equipment that does not function properly is checked separately, the equipment down time and corresponding man-hour utilization can rapidly increase. On the other hand, familiarity with the system reference material, system functional diagram, and fault isolation procedures can lead logically and expeditiously to the specific area of the fault.

All system fault isolation material is interrelated. Its effective use depends on knowing what materials are available, how they are interrelated, and how to cross-reference between materials. To this purpose, this section provides a description of the isolation material that you will use in fault isolation.

**SYSTEM FAULT INDICATOR DIRECTORY (FID).**—The system fault indicator directory facilitates entry into the documentation required for troubleshooting a fault disclosed by a specific indicator during normal operation or system exercise. A typical FID is shown in table 9-2. The material in this FID is grouped by system and further divided alphabetically by equipment, panel, and indicator. A complete listing of indicators (lamps, push-button indicators, dials, and meters), whose status may be associated with a system fault, is included.

The reference provided for each indicator includes a system functional diagram (SFD) and an applicable fault analysis matrix (FAM) reference. The SFD reference pertains to the SFD

**Table 9-2.—Sample Fault Indicator Directory**

| EQUIPMENT | INDICATOR | INDICATOR TYPE | SFD FIGURE REFERENCE & SHEET NO. | SMT/FAM REFERENCE |
|---|---|---|---|---|
| FCS<br>SPG-XX<br>RDP<br>(Cont'd) | PS1 MULTIVOLT | LAMP | 12-13.1 (3) | |
| | PS2 +5V | LAMP | 12-13.1 (3) | |
| | SC ON | LAMP | 12-13.1 (3) | |
| RSC<br>21A1 | CWI GROUP | | | |
| | EMCON/RADHAZ | LAMP | 12-11.5 | |
| | FCS ECM ALERT GROUP | | | |
| | COHERENT ECM RESET | | | |
| | NOISE ECM | | | |
| | NOISE REPEAT | | | |
| | RDP GROUP | | | |
| | ON/OFF | | | W-1, Table 10-2.1 |
| | TEST/READY | LAMP | 12-11.2 | W-1, Table 10-2.1 |
| | SYSTEM STATUS GROUP | | | |
| | CONTROL ALARM | LAMP | 12-11.2 | |
| | GO | LAMP | 12-13.1 (3) | W-1, Table 10-2.1 |
| | PERMISSION TO TEST | LAMP | 12-14.1 (1) | |
| | RDP FAULT | LAMP | 12-13.1 (3) | |
| | TRACK GROUP | | | |
| | EMCON/RADHAZ | LAMP | 12-11.5 | |

55.422

## Table 9-3.—Sample Fire Control System Function Directory

| Function Name (In Alphabetical Order) | Symbol | Origin/ Termination | Appropriate Verifying Test | SFD Figure No | Description Parts 030 Section No. |
|---|---|---|---|---|---|
| Non-Coherent Video | | FM: RDP<br>TO: RSC | | 12-7.2(2) | |
| Normal Track | | FM: RDP | | 12-8.1(1)<br>(2) | |
| Own Ship Heading | Cqo | FM: CS SWBD<br>TO: RDP<br>VIA: PDS | | 12-5.2(4) | |
| Own-Ship Pitch | Eio | FM: CS SWBD<br>TO: RDP<br>VIA: PDS | | 12-5.2(4) | |
| Own-Ship Roll | Zdo | FM: CS SWBD<br>TO: RDP<br>VIA: PDS | | 12-5.2(4) | |
| Permission to Test | | FM: C152<br>TO: RSC<br>RTS<br>VIA: SDC<br>RDP | | 12-14.1(1) | |
| Passive Track | | FM: RDP | | 12-8.1(2) | |
| Preheat Indicator | | FM: CWI XMTR | | 12-11.1(3) | |
| Pretrigger | | FM: RDP<br>TO: RFTTG | | 12-14.2(1)<br>(3) | |
| Pulse Radiate Command | | FM: RDP<br>TO: PULSE XMTR/ RCVR<br>VIA: RSC<br>PULSE PS<br>TO: RTS<br>VIA: RSC | | 12-11.6(1)<br>(2) | |
| Query Command | | FM: ADP<br>TO: RDP | | 12-13.1(4) | |
| Radar Elevation Error | | FM: RDP<br>TO: RSC | | 12-7.2(2) | |
| Radar Evaluation GO/NO-GO | | FM: RDP<br>TO: RTS<br>VIA: RSC | | 12-14.3 | |
| RF Power | | FM: XTMR/RCVR<br>TO: ANT | | 12-7.1(4) | |
| Radar Traverse Error | | FM: RDP<br>TO: RSC | | 12-7.2(2) | |
| RADHAZ | | FM: CONT 178<br>TO: PULSE PS<br>CWI XMTR<br>VIA: RSC | | 12-11.5 | |
| RADHAZ Supply | | FM: PDS<br>TO: CONT 178 | | 12-16.1(1) | |
| Radiate Indicate | | FM: CWI XMTR<br>TO: CONT PS | | 12-11.1(3) | |

55.423

figure used to troubleshoot the fault on the system level, which the individual indicator indicates. The applicable FAM reference is used for troubleshooting and to verify the operational status of the system on an equipment level.

**SYSTEM FUNCTION DIRECTORY.**—A system function directory (table 9-3) is used with the FID. It contains an alphabetical listing of all system functions contained in the SFDs. This directory can be used to start the troubleshooting process when there is no particular indicator associated with a fault.

**SYSTEM FUNCTIONAL DIAGRAM (SFD).**—An SFD (fig. 9-7) contains all primary and secondary circuits necessary for an understanding of the function of a particular mode, loop, or phase of system operation. Each function is shown from source to termination. Data flow is normally from left to right. All serial components of each piece of equipment in the loop that are significant to functional understanding are shown. All readout devices, test points, and so forth, in each equipment that are significant to system troubleshooting are included.

**FAULT ANALYSIS MATRIX (FAM).**—The FAMs and associated troubleshooting procedures are related to each other and to the system maintenance tests (SMTs) and provide maintenance personnel with an effective troubleshooting package. To keep this material as specific as possible, the following assumptions are made:

1. All equipment is properly energized and indicator lamps have been tested.
2. Associated switchboards are set up correctly, all power lamps are lit, and no fuses are blown.
3. Troubleshooting faults do not begin until the test is completed, if possible. This procedure allows the technician to troubleshoot several related faults simultaneously, reducing troubleshooting time.
4. Troubleshooting faults should occur in the same sequence in which the faults are discovered; for example, a fault discovered in step 9 of an SMT should be corrected before a fault discovered in step 14. Adherence to this sequence for correcting faults is desirable because the initial fault observed during a test may be the cause of those observed thereafter; thus, correcting the initial fault may correct those observed later in the test sequence.

The FAM (table 9-4) is arranged in tabular form to provide a quick cross-reference of troubleshooting aids and reference material. In addition to the Step and Function columns, table 9-4 contains the following columns:

Source column. This column lists the function source and test points, if applicable.

Intermediate unit(s) column. This column lists units between source and destination.

Related SMT(s) column. This column lists other SMT(s) and associated step(s) in which the parameter in the function column is tested, if applicable.

References column. This column lists available system/equipment reference material that can most readily be used. An applicable SFD is the first listing.

Suggested Fault Isolation Procedures column. This column provides suggested troubleshooting procedures for fault isolation; for example, applicable self-tests, alternate system configuration/substitution, and so forth. It should be emphasized that these are suggested troubleshooting procedures and are not meant to preclude or remove judgment for troubleshooting from the technician. The intent of the FAM is to serve as a troubleshooting aid while allowing latitude for personal preference as to the approach and technique applied.

**SAMPLE TROUBLESHOOTING PROBLEM.**—To show how troubleshooting documentation is used to isolate faults, a sample problem is provided with corresponding fault analysis procedures using samples of fault isolation materials covered previously in this chapter. The sample problem and associated fault analysis procedures are based on a fault revealed during system maintenance test (SMT) W-1.

Prior to the hypothetical fault, it is assumed that all turn-on procedures and preliminary test steps have been accomplished with no apparent malfunctions indicated. No PERMISSION TO TEST indication is observed at the radar set console (RSC).

After verification of all test setups, the test coordinator then refers to the FAM for SMT W-1

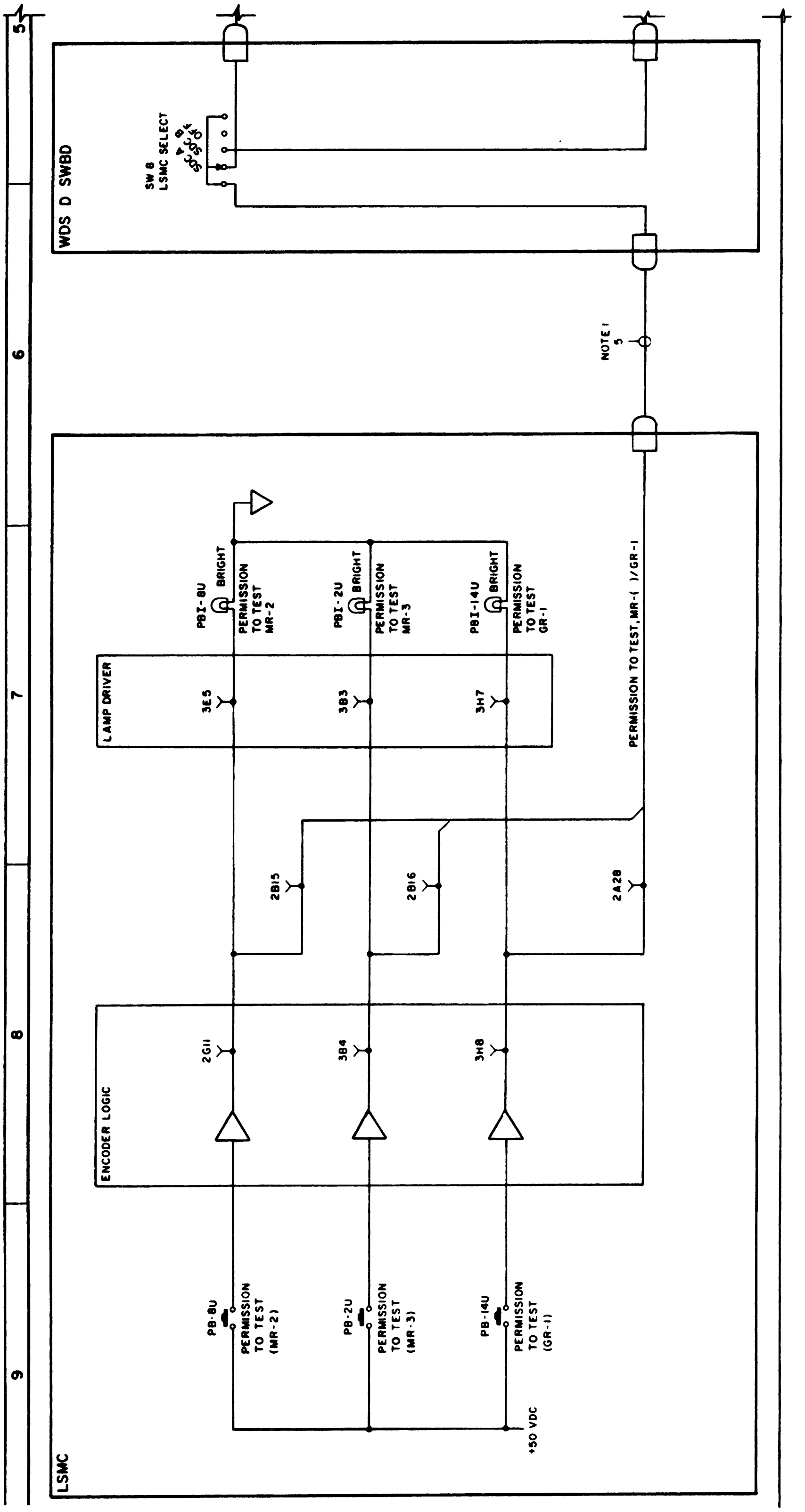

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Figure 9-7.—Sample weapon system functional diagram.

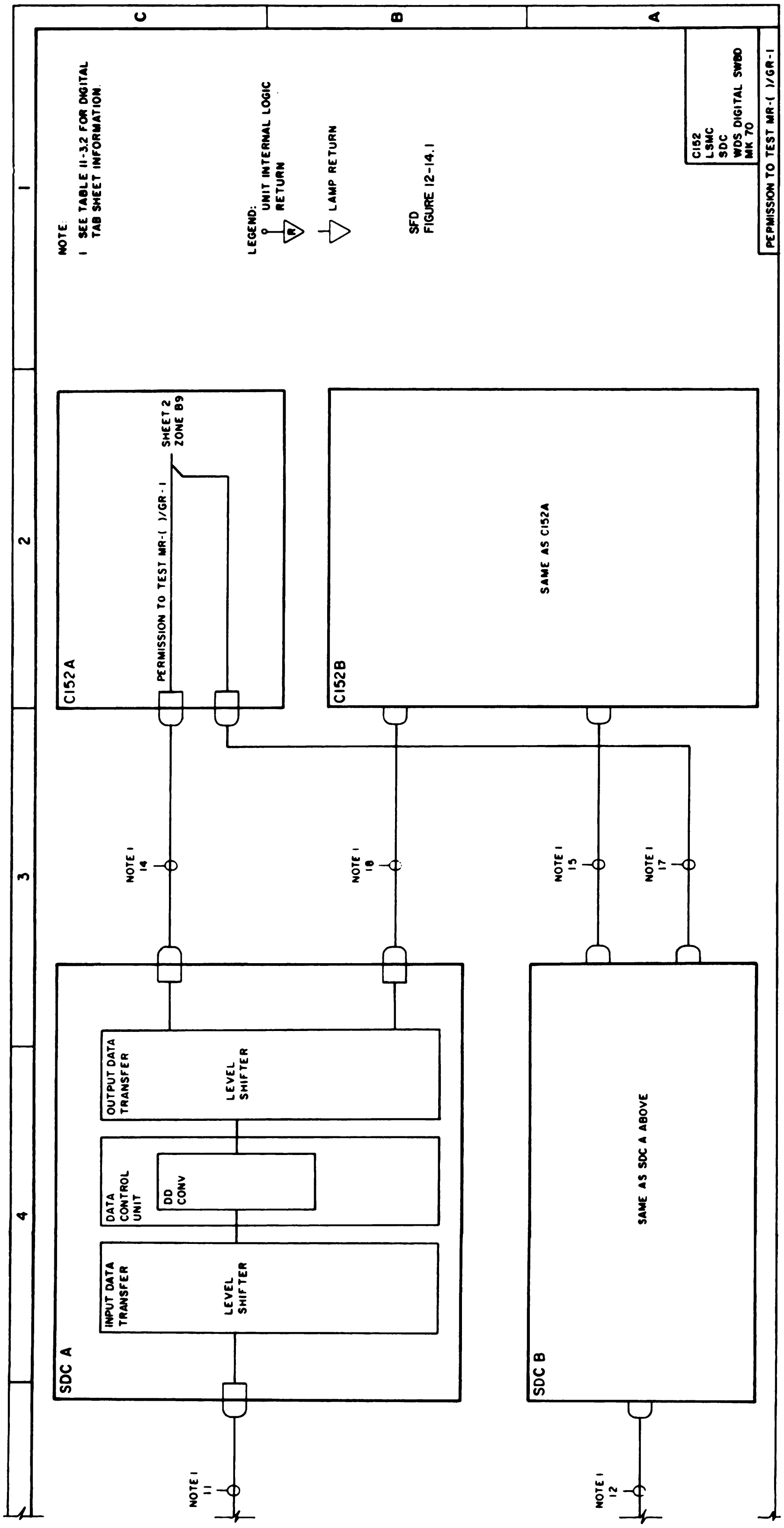

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Figure 9-7.—Sample weapon system functional diagram—Continued.

Table 9-4.—Sample Fault Analysis Matrix

| STEP | FUNCTION | SOURCE | INTERMEDIATE UNITS | RELATED SMTS | REFERENCES | SUGGESTED FAULT ISOLATION PROCEDURES |
|---|---|---|---|---|---|---|
| 1.a | Restore/Delete MR-( ) | FCSC | TDS C&C<br>SWBD<br>C152 | W-2 | Figure 11-22.5 | Perform WDS CMPTR diagnostics. |
| 1.b | MR-( ) AVAIL | FCSC | TDS C&C<br>SWBD | W-2 | Figure 11-21.6 | Perform WDS CMPTR diagnostics. |
| 2 | MR-( ) Go | C152 | SDC<br>WDS D SWBD<br>LSMC | W-2 | Figure 11-13.3 | Perform WDS CMPTR diagnostics. |
| 3 | Own-Ship Display<br>a. M at Own Ship<br>b. Own Ship Heading<br>c. Launcher Blind Zone<br>d. Launcher Bearing<br>e. MR-( ) Symbol | C152 | WDS D SWBD |  | Figure 11-24.1 | Perform WDS CMPTR diagnostics. |
| 4 | Permission to Test | LSMC | WDS CS SWBD<br>SDC<br>C152<br>RDP | W-2 | Figure 12-14.1 | a. Perform C-TASC IM/CB Test 877.<br>b. Perform continuity check between RDP (J11-c) and RSC (J4-c).<br>c. Perform ground check at RSC (J4-c) and P4-c).<br>d. Perform SDC Signal Monitoring and Fault Monitoring (SM/FM) Tests. |

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(table 9-4), which lists all SMT response steps (column 1) and the associated function that is tested (column 2).

From columns 3 and 4, the functions, sources, and intermediate units can readily be determined.

The References column of table 9-4 lists SFD figure 12-14.1 (shown in fig. 9-7) as references for the permission to test function. By using the available reference material, the test coordinator can proceed to column 7 and implement the suggested fault isolation procedures. As previously stated, it is again emphasized that these are suggested troubleshooting procedures and are not meant to preclude or remove judgement from the technician.

In column 7, step a, C-TASC (a computer diagnostic program) is used to determine if logical output voltages are being (1) generated at the radar data processor (RDP) and (2) transmitted to the radar set console (RSC). The succeeding fault isolation procedures listed in the FAM are then accomplished as required until the casualty is found or isolated to an equipment.

If the preceding problem had arisen at any time other than during a scheduled test, the system FID (table 9-2) and/or the FCS function directory (table 9-3) could be used.

When the FID is used to facilitate solutions of problems encountered during normal operation or weapon system exercises other than scheduled testing, the faulty indication is identified and located in the Indicator column for the associated equipment listed in the Equipment column (table 9-2).

Using the same hypothetical fault describe above, refer to the sample FID (table 9-2) and locate the RSC in the Equipment column and PERMISSION TO TEST in the Indicator column. The applicable SFD and FAM may then be referred to for trouble analysis. At the discretion of the test coordinator, the equipment may be set up as required in the referenced FAM, and the associated trouble analysis procedures accomplished as described in the above paragraphs.

Where there is no readily identifiable indicator for a given function, reference may be made to the System Function Directory to cross-reference the applicable SFD.

**EQUIPMENT TROUBLESHOOTING DOCUMENTATION.**—Equipment OPs contain a wealth of documentation that enables rapid localization of faults that have been traced to a particular piece of equipment. The documentation includes (but is not limited to) fault logic diagrams (FLD), signal flow diagrams, pyramid diagrams, relay and lamp indexes, and relay lamp ladder diagrams. In addition, maintenance turn-on procedures (table 9-5) are provided for energizing the equipment. These procedures contain references to troubleshooting documents that are to be used if a given step of the procedure cannot be performed satisfactorily. In the following

**Table 9-5.—Sample Maintenance Turn-On-Procedure**

| STEP | PROCEDURE | OBSERVATION | REF. |
|---|---|---|---|
| 1 | Perform preliminary preparations in accordance with paragraph 2-17. | | |
| 2 | At Control-Power Supply perform the following: | | |
| | a. Depress OFF-ON pushbutton switch 14A2S5. | ON lit | 4-5 |
| | b. Observe PREHEAT indicator of PREHEAT switch 14A2S8. | PREHEAT lit | 4-5 |
| | c. Depress COMMAND STANDBY pushbutton switch 14A2S9. | COMMAND lit | 4-5 |
| | | STANDBY lit after approximately 5 minutes | 4-5 |
| | d. Observe LOW VOLTAGE lamp 14A2DS2. | Lit | 4-6 |

paragraphs, some of the primary equipment troubleshooting documentation are covered.

**Fault Logic Diagrams.**—A fault logic diagram (FLD) is used to speed troubleshooting by requiring the technician to answer a branching series of questions about an observed system fault (fig. 9-8). The questions, which permit only yes or no answers, pertain primarily to the status of external indications (lamps, dials, meters, scope displays, and so forth), but they may also include internal indications at key test points. By a process of elimination, the technician is led to the area of probable trouble and is referred to equipment troubleshooting documents.

**Signal Flow Diagrams.**—Signal flow diagrams (fig. 9-9) show the signal flow from an input to

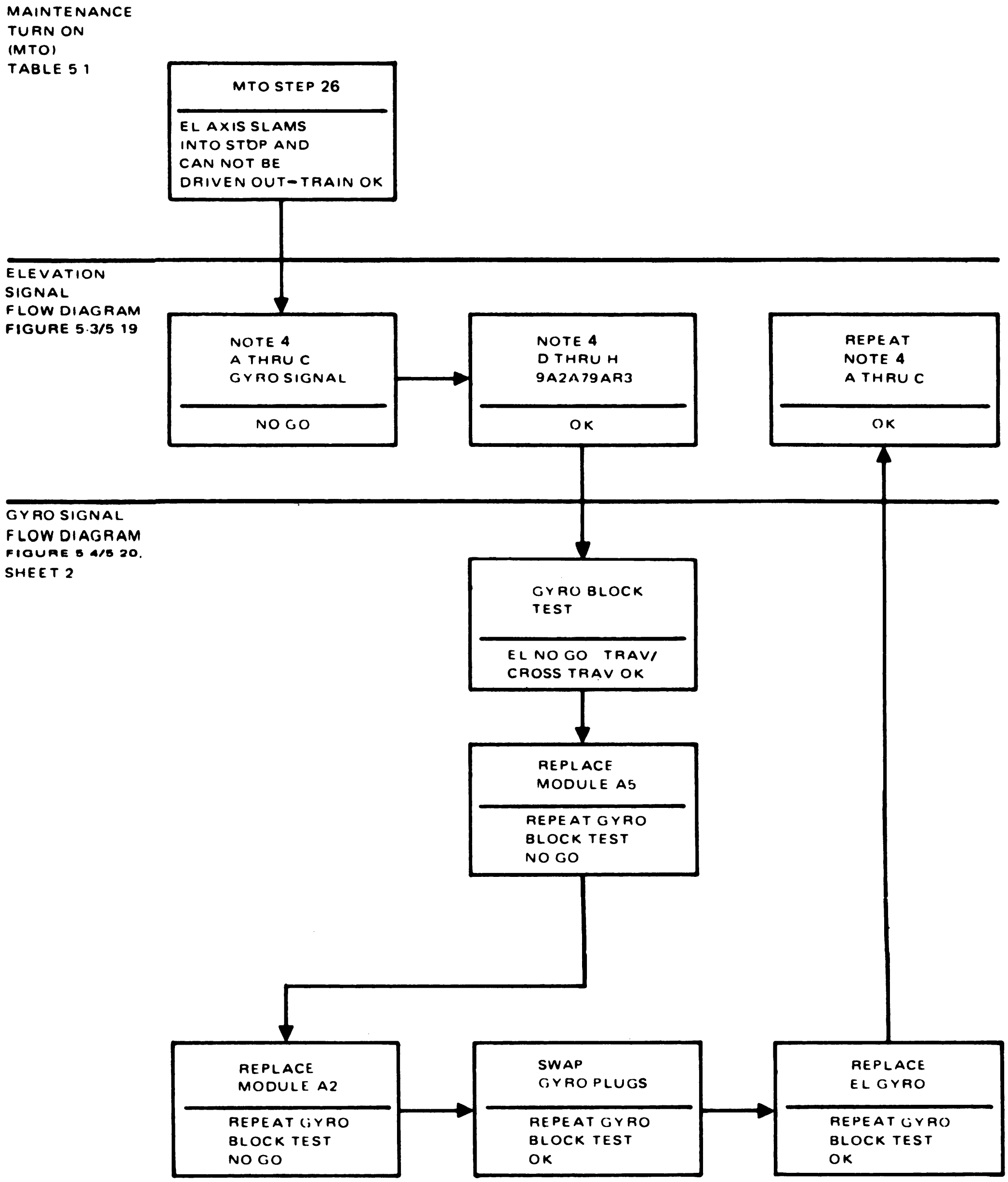
MAINTENANCE TURN ON (MTO) TABLE 5 1
MTO STEP 26
EL AXIS SLAMS INTO STOP AND CAN NOT BE DRIVEN OUT–TRAIN OK
ELEVATION SIGNAL FLOW DIAGRAM FIGURE 5-3/5 19
NOTE 4 A THRU C GYRO SIGNAL
NO GO
NOTE 4 D THRU H 9A2A79AR3
OK
REPEAT NOTE 4 A THRU C
OK
GYRO SIGNAL FLOW DIAGRAM FIGURE 5 4/5 20, SHEET 2
GYRO BLOCK TEST
EL NO GO TRAV/ CROSS TRAV OK
REPLACE MODULE A5
REPEAT GYRO BLOCK TEST NO GO
REPLACE MODULE A2
REPEAT GYRO BLOCK TEST NO GO
SWAP GYRO PLUGS
REPEAT GYRO BLOCK TEST OK
REPLACE EL GYRO
REPEAT GYRO BLOCK TEST OK

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Figure 9-8.—Sample fault logic diagram.

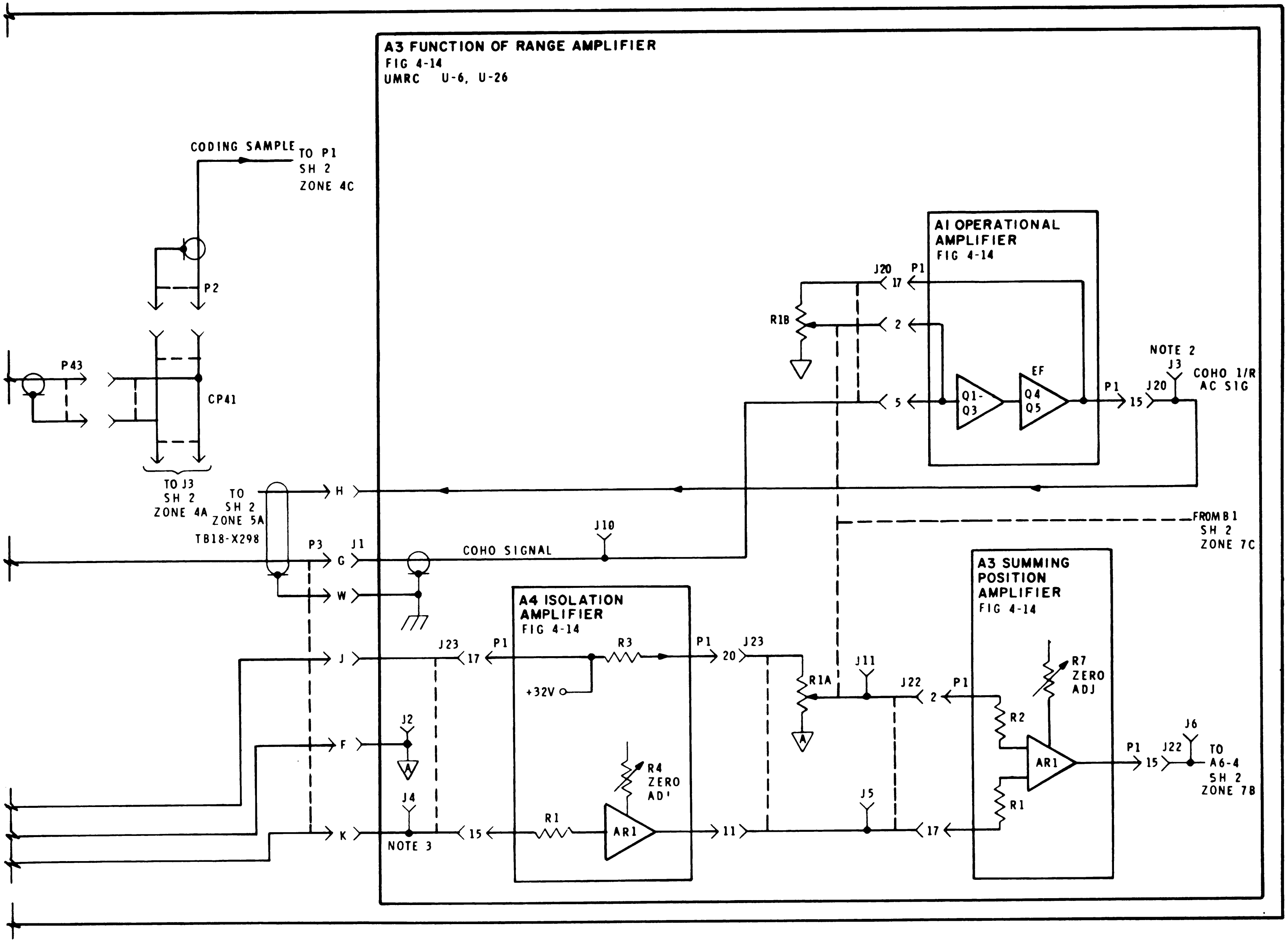

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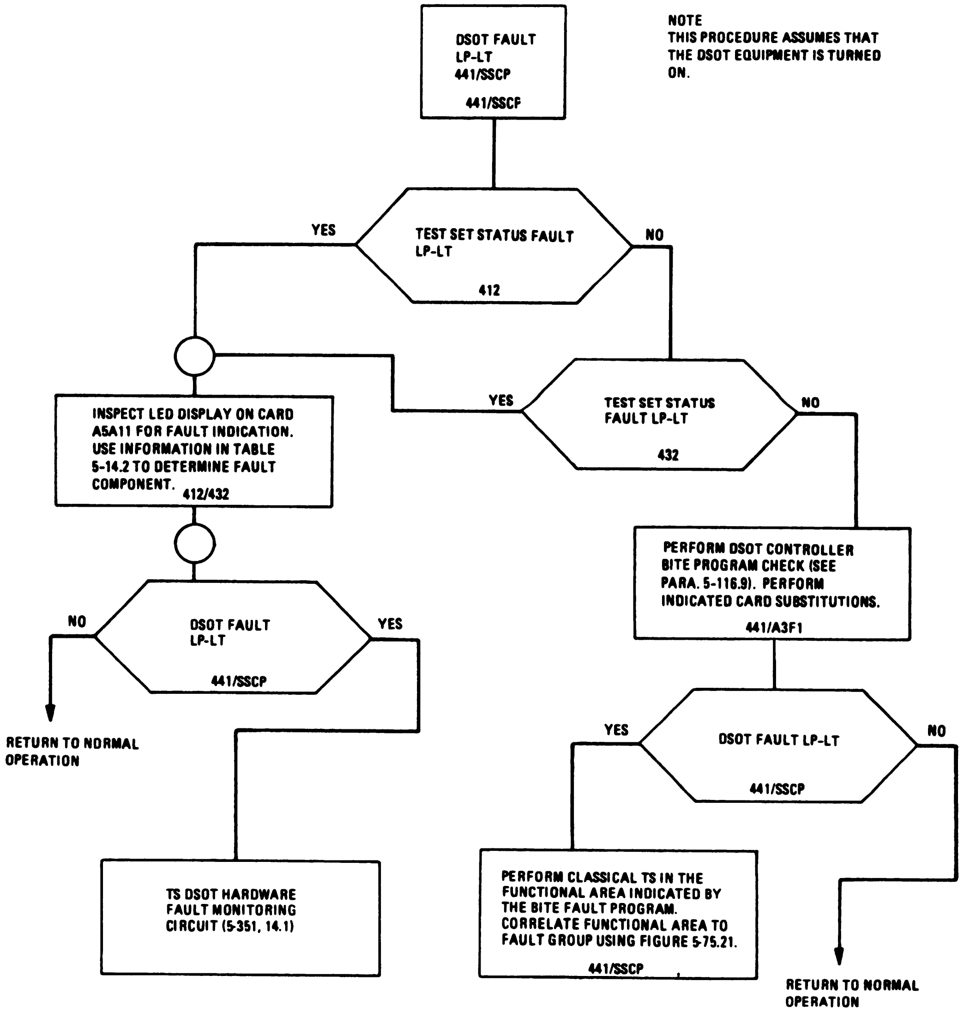
Figure 9-9.—Sample signal flow diagram.

an output function. Adjustment procedures, replacement procedures, and schematics are referenced in the signal flow diagram to provide the technician with quick access to the appropriate maintenance requirements cards and related troubleshooting documentation.

**Pyramid Diagrams.**—Pyramid diagrams (fig. 9-10) deal with the interdependency of the subassemblies essential to each function of a piece of equipment. The pyramid starts with an output functions and, for a given local test setup, lists the values and allowable tolerances of that function. Subsequent checks of the various inputs that affect the function are contained in blocks, which radiate downward from the statement of the function. The blocks contain recommended corrective action if the check of the input is at fault. Each leg of the pyramid is terminated by an input and reference to other pyramids or related documents. Thus, the equipment troubleshooting pyramids should enable you to quickly localize faults and perform the necessary corrective action by referencing the associated material.

**Relay and Lamp Indexes.**—The relay and lamp indexes (table 9-6) list all of the lamps and


DSOT FAULT
LP-LT
441/SSCP
441/SSCF
NOTE
THIS PROCEDURE ASSUMES THAT THE DSOT EQUIPMENT IS TURNED ON.
YES
TEST SET STATUS FAULT
LP-LT
412
NO
INSPECT LED DISPLAY ON CARD A5A11 FOR FAULT INDICATION. USE INFORMATION IN TABLE 5-14.2 TO DETERMINE FAULT COMPONENT.
412/432
YES
TEST SET STATUS
FAULT LP-LT
432
NO
PERFORM DSOT CONTROLLER BITE PROGRAM CHECK (SEE PARA. 5-116.9). PERFORM INDICATED CARD SUBSTITUTIONS.
441/A3F1
NO
DSOT FAULT
LP-LT
441/SSCP
YES
RETURN TO NORMAL OPERATION
YES
DSOT FAULT LP-LT
441/SSCP
NO
TS DSOT HARDWARE FAULT MONITORING CIRCUIT (5-351, 14.1)
PERFORM CLASSICAL TS IN THE FUNCTIONAL AREA INDICATED BY THE BITE FAULT PROGRAM. CORRELATE FUNCTIONAL AREA TO FAULT GROUP USING FIGURE 5-75.21.
441/SSCP
RETURN TO NORMAL OPERATION

55.429

Figure 9-10.—Sample pyramid diagram.

Table 9-6.—Sample Relay Index

| Relay | Function | Coil Supply | Figure | | Sheet | Zone | Contact Location | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Figure | | Sheet | Zone |
| | | | Mod 5 | Mod 6 | | | Mod 5 | Mod 6 | | |
| 9A4K2 | Missile in Flight (KMIF) | 50 vdc | 5-8 | 5-24 | 1 | B6 | 5-9 | 5-25 | 1 | C7 |
| | | | | | | | 5-6 | 5-22 | 1 | C1 |
| | | | | | | | 5-7 | 5-23 | 1 | A5 |
| | | | | | | | 5-8 | 5-24 | 1 | B5 |
| 9A4K3 | Electronics Unplugged Interlock (KEUI) | 50 vdc | 5-7 | 5-23 | 2 | A2 | 5-7 | 5-23 | 2 | A1 |
| | | | | | | | 5-7 | 5-23 | 1 | A1 |
| 9A4K4 | Electronic Voltage Supply (KEVS) | 50 vdc | 5-7 | 5-23 | 2 | A2 | 5-9 | 5-25 | 1 | C7 |
| | | | | | | | 5-7 | 5-23 | 2 | A1 |
| | | | | | | | 5-7 | 5-23 | 1 | A1 |
| 9A4K5 | Director Running (KDR) | 50 vdc | 5-8 | 5-24 | 1 | B4 | 5-8 | 5-24 | 1 | B1. B2 |
| | | | | | | | 5-9 | 5-25 | 1 | C7 |
| 9A4K6 | Director Test (KDT) | 50 vdc | 5-8 | 5-24 | 1 | B6 | 5-8 | 5-24 | 1 | B2, B3 |
| | | | | | | | 5-10 | 5-26 | 1 | C9 |
| 9A4K7 | Train Overspeed (KTOS) | 50 vdc | 5-6 | 5-22 | 2 | A4 | 5-9 | 5-25 | 1 | B8 |
| | | | | | | | 5-6 | 5-22 | 2 | A4. B1, B3 |
| 9A4K8 | Elevation Overspeed (KEOS) | 50 vdc | 5-6 | 5-22 | 2 | A4 | 5-9 | 5-25 | 1 | B8 |
| | | | | | | | 5-6 | 5-22 | 1 | B2 |
| | | | | | | | 5-6 | 5-22 | 2 | A4. B1. B2 |
| 9A4K9 | Train Overspeed (KTOS) | 50 vdc | 5-6 | 5-22 | 2 | A4 | 5-6 | 5-22 | 2 | A6 |
| | | | | | | | 5-6 | 5-22 | 1 | B2, B3 |
| 9A4K10 | Power Amplifier Test (KPAT) | 50 vdc | 5-10 | 5-26 | 1 | C9 | 5-11 | 5-27 | 1 | C7 |
| 9A4K11 | Train Control (KTC) | 115 vac | 5-9 | 5-25 | 1 | B8 | 5-9 | 5-25 | 1 | A5, B9 |
| | | | | | | | 5-11 | 5-27 | 1 | C8 |

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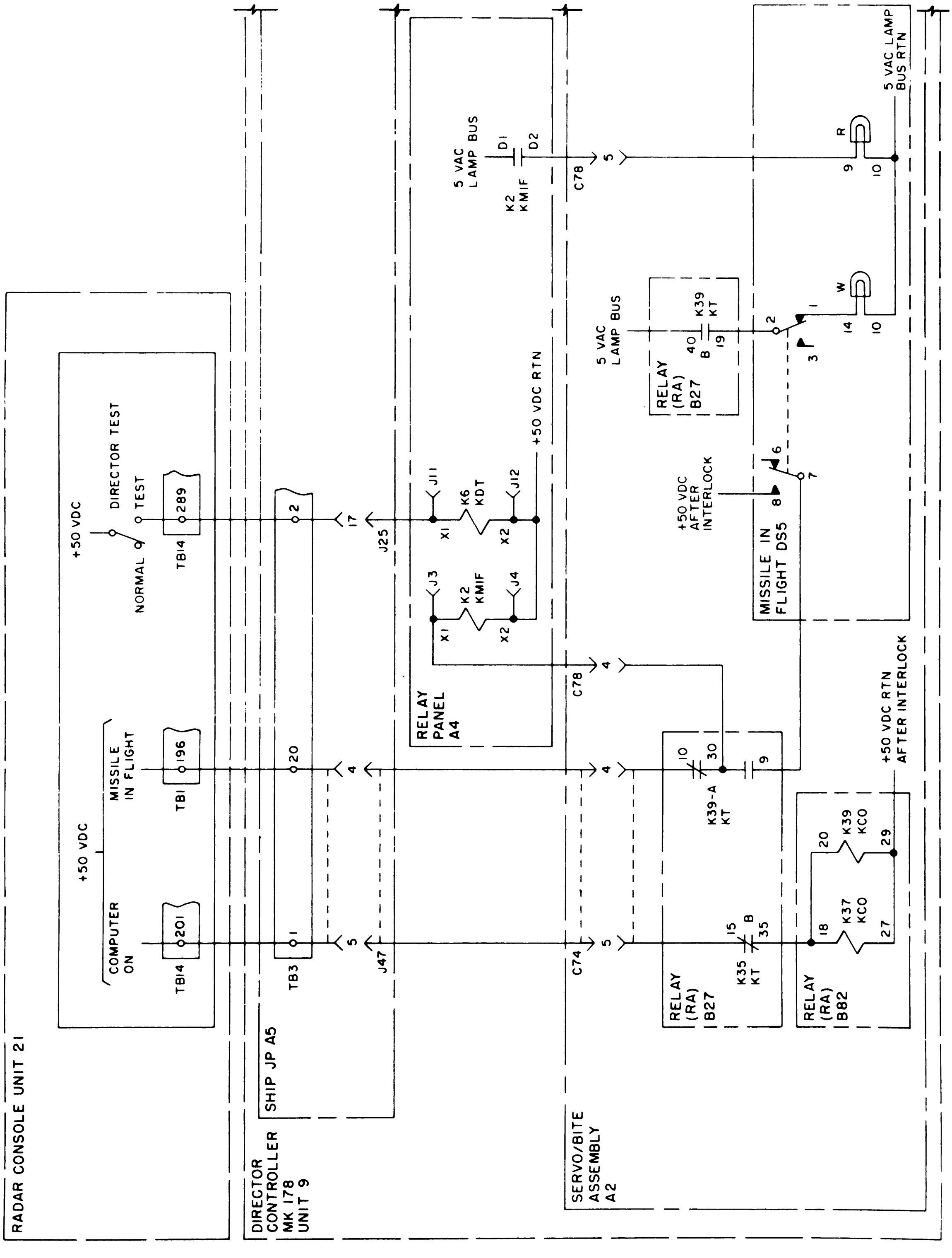

Figure 9-11.—Sample relay lamp ladder diagram.

relays shown on the troubleshooting diagrams. The indexes list, in unit designation sequence, all relay coils and related switches and indicator lamps. They cross-index by figure, sheet, and zone the location of the relay coil and indicator lamp energizing paths.

**Relay Lamp Ladder Diagrams.**—Relay lamp ladder diagrams (fig. 9-11) show the energizing paths for relays and indicator lamps that are not covered by signal flow diagrams. They are used along with relay and lamp indexes.

The relay lamp ladder diagram traces the energizing path for the relay coil or indicator lamp from a common interface point appearing on both the power distribution diagram and the ladder diagram. It traces through the equipment, to the respective relay coil or indicator lamp, and to a common return power interface. The relay lamp ladder diagram shows cabling, terminal connections, relay contacts, switches, and lamps in the energizing path.

The relay lamp ladder diagram is intended for use as a troubleshooting support document for the signal flow diagram and the maintenance turn-on procedure. It is also to be used as the prime troubleshooting document for equipment switching problems.

**Sample Equipment Troubleshooting Problem.**—Because of the inherent differences in fire control equipment, each fire control system has its own troubleshooting philosophy; however, they all use the basic troubleshooting documentation (or a modification or combination of the basic documentation) covered in this chapter. The sample problem here uses the checkout-procedure, problem-directory, pyramid-diagram method of troubleshooting.

In this method, the technician sets up, adjusts, and verifies equipment operation according to a set of steps in the checkout procedures shown in figure 9-12. If the function being tested at a particular step fails, the technician refers to that same numbered step in the

CHECKOUT PROCEDURES.

Check out the radar video processing and distribution system as follows:

Step 1. Set up radar video processing and distribution system troubleshooting initial conditions according to paragraph 7-13-8.

Step 2. At unit 1, Set SWEEP RANGE (NMI) switch to 5.

Step 3. Adjust VIDEO GAIN and INTENSITY for optimum video and sweep presentation.

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Step 27. Set M/N SELECT switch to 10, and verify that all lamps on 25A38 are lit.

Step 28. Set M/N SELECT switch to 4, and verify that all lamps on 25A38 are out.

Step 29. Set M/N SELECT switch to 5, and verify that all lamps on 25A38 are out.

●

●

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Figure 9-12.—Sample checkout procedure.

**Table 9-7.—Sample Problem Directory**

| Failed Checkout Procedure Step No. | Indication | Procedure |
|---|---|---|
| 3 | Adjusting VIDEO GAIN and INTENSITY controls does not provide optimum video and sweep presentation. | Refer to PPI display system troubleshooting, section 7-15. |
| 4 | Type 1 synthetic raw video is not present or is not well defined. | Refer to figure 7-13-1. |
| 5 | ACQUIRE 1 does not light green. | Refer to operator-to-computer buffer system troubleshooting, section 7-5. |
| ●<br>●<br>● | ●<br>●<br>● | ●<br>●<br>● |
| 27 | All lamps on 25A38 out. | Set S/P BYPASS switch to On.<br>If lamps light, fault in S/P Converter 25A38A26, figure 8-9-4 sheet 1.<br>If lamps stay out, fault in M/N SELECT Switch 25A38S5 or Test Board 25A38A31, figure 8-9-4 sheet 3. |
|  | One or more lamps on 25A38 out. | Refer to figure 7-13-3. |
|  | CLR PLOT VID lamp out. | Fault in P/S Converter 25A38A27 or Test Board 25A38A31, figure 8-9-4 sheet 3. |
| ●<br>●<br>● | ●<br>●<br>● | ●<br>●<br>● |

problem directory (table 9-7) to isolate the faulty component.

In our sample troubleshooting problem, the faulty component is Test Board 25A38A31. To isolate this component, the technician performs the checkout procedures shown in figure 9-12. At step 27, the technician observes that none of the lamps on 25A38 are lit. From here, the technician proceeds to the problem directory (table 9-7) step 27, where he is directed to set the S/P BYPASS switch to ON. After doing this, he notices that more than one lamp is out on 25A38. The problem directory refers the technician to the Incorrect Lamp Indicator Pyramid Diagram 7-13-3 shown in figure 9-13. Here, the technician follows the instructions outlined in the dashed blocks and answers the questions in the solid block. Eventually, the technician is instructed to

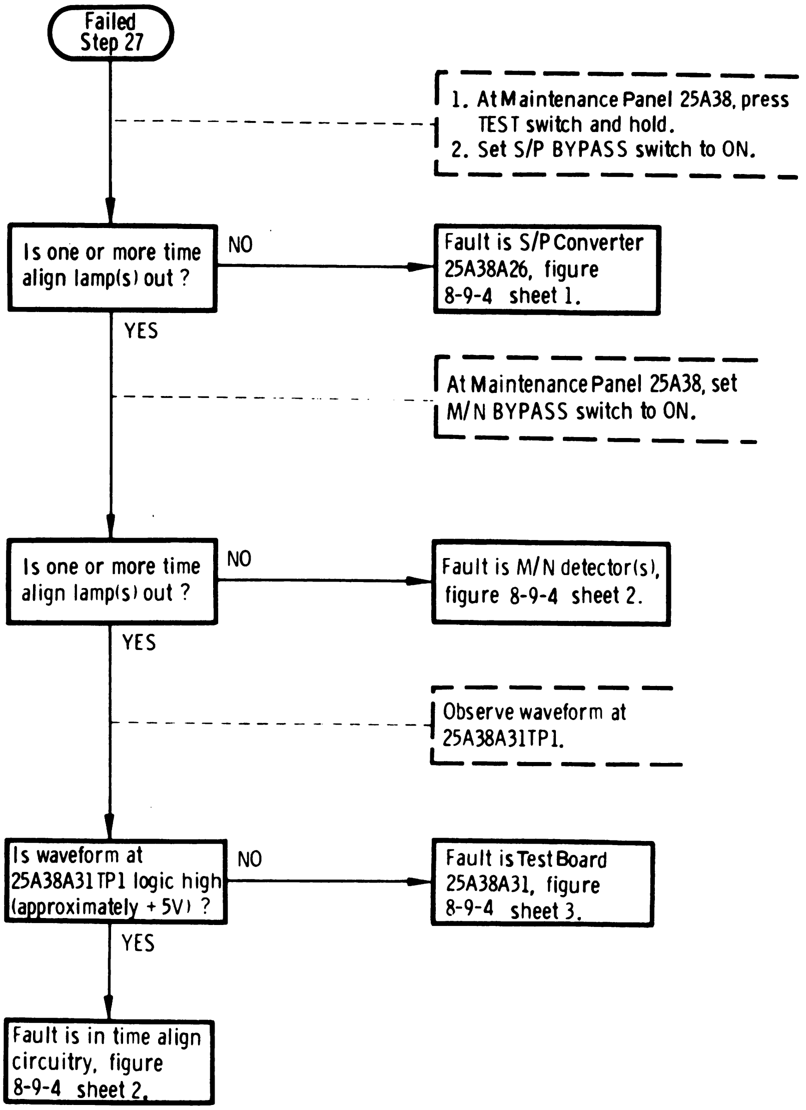
Failed Step 27
1. At Maintenance Panel 25A38, press TEST switch and hold.
2. Set S/P BYPASS switch to ON.
Is one or more time align lamp(s) out ?
NO
Fault is S/P Converter 25A38A26, figure 8-9-4 sheet 1.
YES
At Maintenance Panel 25A38, set M/N BYPASS switch to ON.
Is one or more time align lamp(s) out ?
NO
Fault is M/N detector(s), figure 8-9-4 sheet 2.
YES
Observe waveform at 25A38A31TP1.
Is waveform at 25A38A31TP1 logic high (approximately +5V) ?
NO
Fault is Test Board 25A38A31, figure 8-9-4 sheet 3.
YES
Fault is in time align circuitry, figure 8-9-4 sheet 2.

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Figure 9-13.—Sample troubleshooting pyramid diagram.

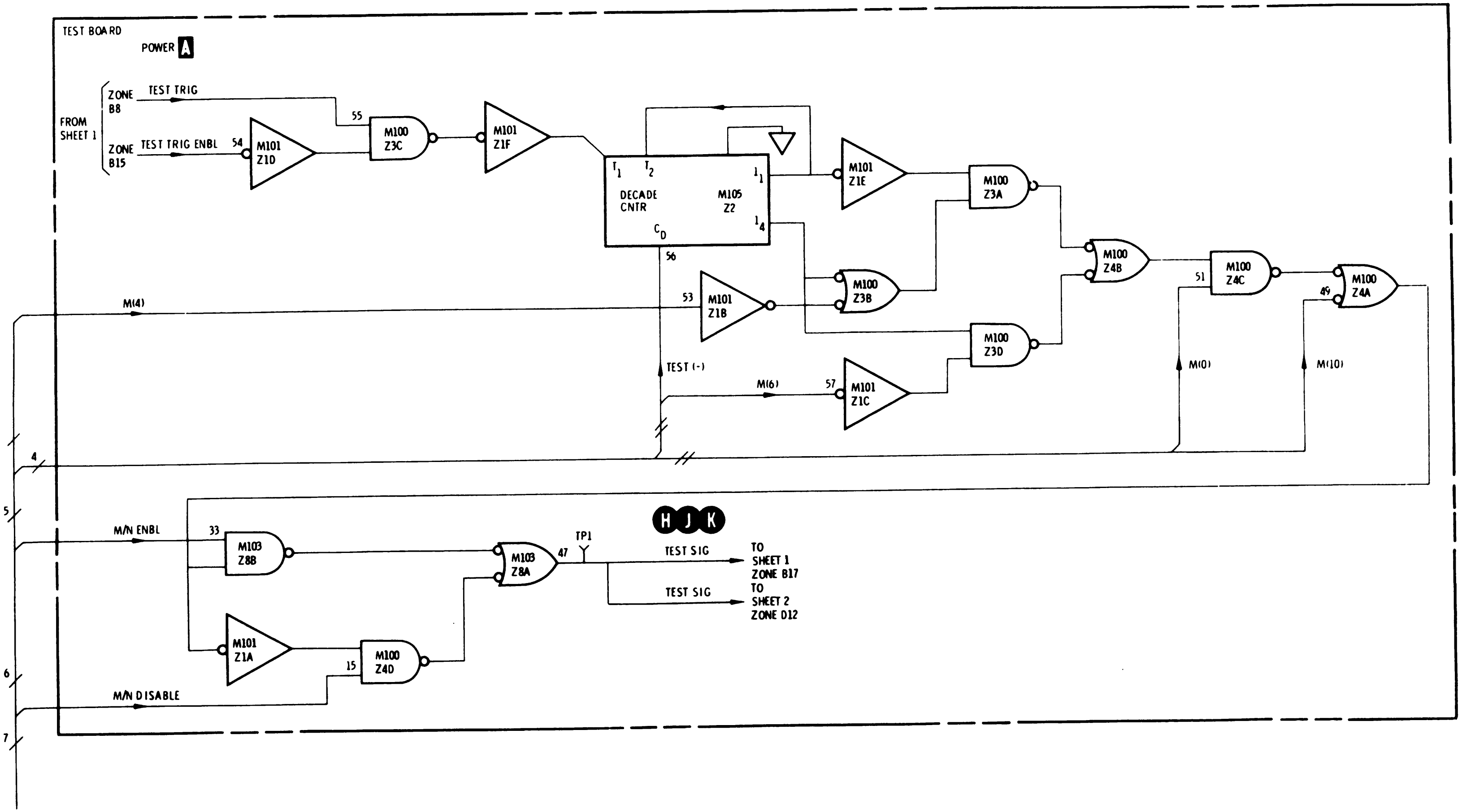

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Figure 9-14.—Sample troubleshooting SFD.

measure the voltage at 25A38A31 TPI (fig. 9-14). A zero-voltage reading at this test point indicates that Test Board 25A38A31 is the faulty component. The technician replaces the circuit board and verifies correct operation by repeating step 27 in the checkout procedures.

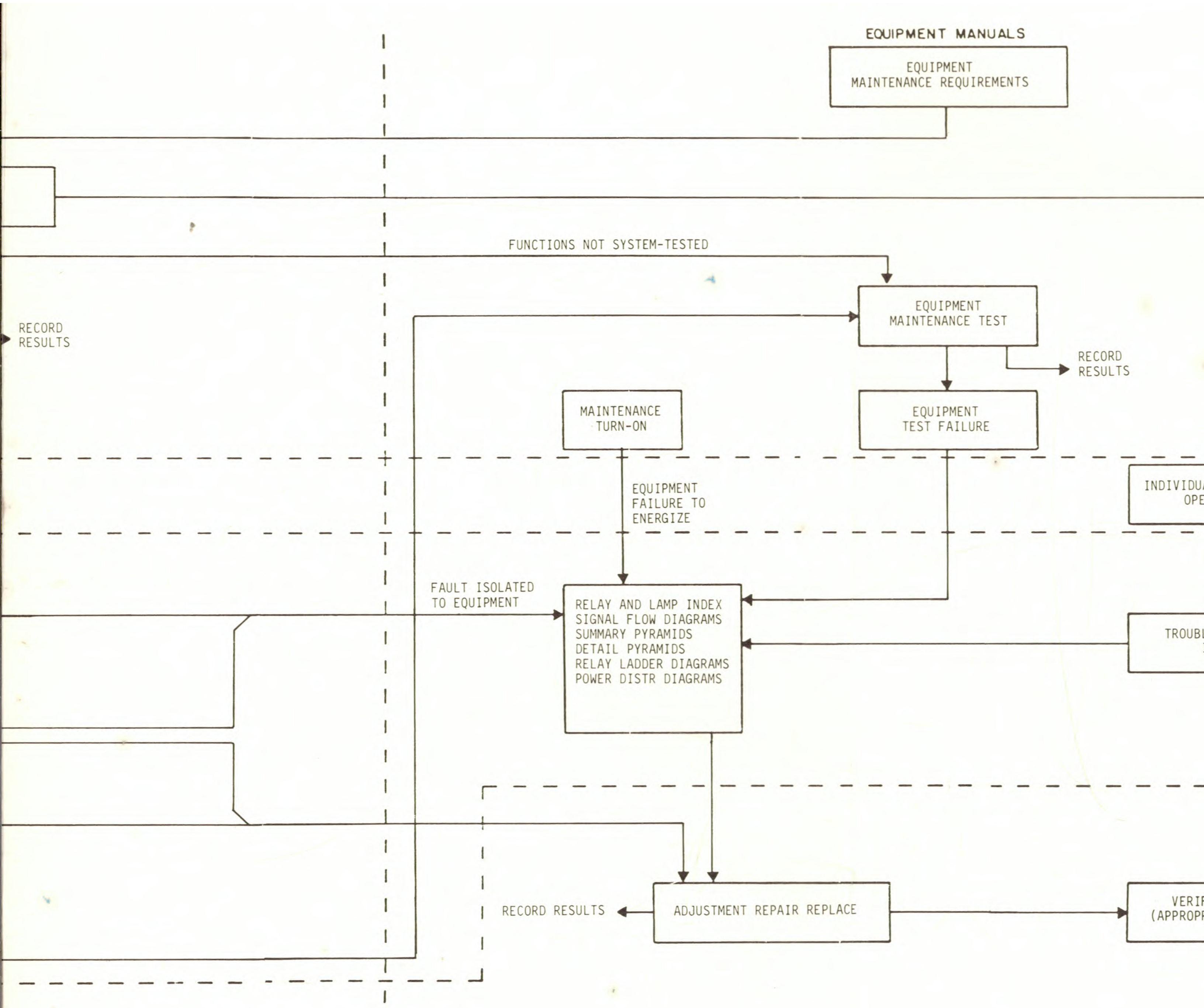
## SUMMARY

The trend in fire control system testing is toward the total combat system approach. In this approach, your fire control system is a subsystem of the ship's combat system. As an FC2, you will be intimately involved in combat system testing; thus, you need to be knowledgeable of other subsystems aboard ship. A good tool for learning other subsystems is the OCSOT.

The integrated maintenance concept consists of scheduling and testing the combat system on three mutually supporting levels: combat system level, subsystem level, and equipment level. Integrating these level of tests into the PMS system enables more efficient management of the entire combat system maintenance efforts. The integrated maintenance concept is the most effective means of achieving the goals of PMS.

Fault isolation is the systematic application of the appropriate fault isolation tools to isolate a fault (or malfunction) to a specific unit. Fault isolation tools include subsystem tests, equipment tests (on-line and off-line tests), and maintenance support documentation.

Troubleshooting documentation is designed to help you rapidly isolate/localize malfunctions down to a defective unit. Best results are obtained when these documentations are used systematically. Systematic troubleshooting requires a detailed knowledge of the available troubleshooting aids. This knowledge is acquired by the application and study of equipment OPs.



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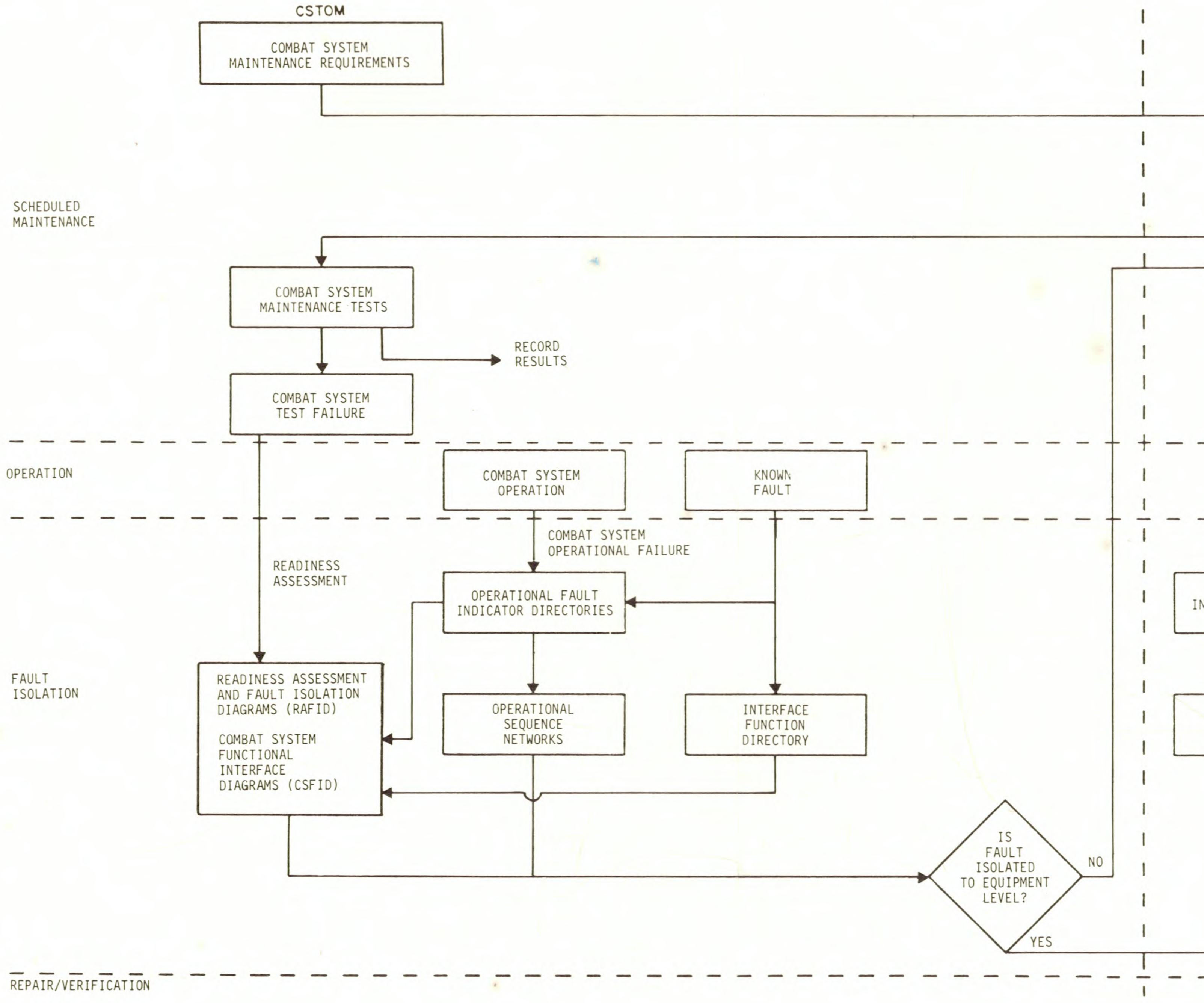
grated maintenance concepts.


CSTOM
COMBAT SYSTEM MAINTENANCE REQUIREMENTS
SCHEDULED MAINTENANCE
COMBAT SYSTEM MAINTENANCE TESTS
RECORD RESULTS
COMBAT SYSTEM TEST FAILURE
OPERATION
COMBAT SYSTEM OPERATION
KNOWN FAULT
COMBAT SYSTEM OPERATIONAL FAILURE
READINESS ASSESSMENT
OPERATIONAL FAULT INDICATOR DIRECTORIES
FAULT ISOLATION
READINESS ASSESSMENT AND FAULT ISOLATION DIAGRAMS (RAFID)
COMBAT SYSTEM FUNCTIONAL INTERFACE DIAGRAMS (CSFID)
OPERATIONAL SEQUENCE NETWORKS
INTERFACE FUNCTION DIRECTORY
IN
IS FAULT ISOLATED TO EQUIPMENT LEVEL?
NO
YES
REPAIR/VERIFICATION

# APPENDIX I

# GLOSSARY

A-SCOPE.—A radar display on which slant range is shown as the distance along a horizontal trace.

ACCELERATION SERVO SYSTEM.—A servo system that controls the acceleration (rate of change in velocity) of a load.

ACCELEROMETER.—A device that measures acceleration to which it is subjected and develops a signal proportional to it.

ACCUMULATOR.—A register in a computer in which the result of a given operation is temporarily stored.

ACQUISITION.—Operational phase of a fire control or track radar during which the radar system searches a small volume of space in a prearranged pattern.

ACTIVE JAMMING.—Intentional radiation or reradiation of electromagnetic energy with the intention of impairing the use of that band.

ADDEND.—In addition, the number added to a second number called the augend.

ADDER.—A digital circuit that performs the addition of numbers.

ADDRESS.—The location of a given storage cell in a memory.

AIDED TRACKING.—A system of tracking a signal in azimuth, elevation, or range, in which a constant rate of motion of the tracking mechanism is maintained by mechanical means so that an equivalent constant rate of motion of the target can be followed.

AIR-CONTROL PANEL.—Panel that monitors the dry-air input at each user equipment.

ALIGNMENT.—Procedures that establish the prescribed angular relationship between the combat system equipment and attain accurate transmission of equipment position quantities. The prescribed angular relationship between equipments is established by leveling each equipment to an own-ship reference plane and aligning each equipment to an alignment reference.

ALIGNMENT CHECKS.—Procedures that are conducted to verify that an equipment is aligned to its reference within a specified tolerance. Alignment checks are made by comparing the indicated angular position of the nonreference equipment to that of the alignment reference when their pointing lines are parallel.

ALIGNMENT REFERENCE.—An equipment used as the reference when aligning other combat system equipment in train and elevation.

ALIGNMENT REQUIREMENTS.—Alignment requirements are based on the accuracy of the equipment and subsystems of the total combat system. Equipment and subsystem alignment requirements are dictated by the overall requirement of the operational mode that demands the most accurate alignment between equipments.

ALIGNMENT TELESCOPE.—An optical telescope mounted on a piece of equipment for alignment purposes. The optical axis of the telescope represents the mechanical angular position of the equipment.

ALTITUDE.—Vertical distance of an aircraft or object above a given reference, such as ground or sea level.

AMBIGUOUS RETURNS.—Echoes that exceed the PRT of a radar and appear at incorrect ranges.

ANALOG.—Being continuous or having a continuous range of values, as opposed to a discrete set of values.

AND GATE.—A digital logic circuit in which a HIGH output occurs if, and only if, all the inputs are HIGH.

ANGULAR POSITION.—The counterclockwise angular displacement of a synchro rotor, measured in degrees from its electrical zero position, as viewed from the shaft extension end of the synchro.

ANTENNA BEAMWIDTH.—Angular width of a radar beam measured between half-power points.

ANTENNA SYSTEM.—Routes rf energy from the transmitter, radiates the energy into space, receives echoes, and routes the echoes to the receiver.

ANTIJAMMING CIRCUIT.—Electronic circuit used to minimize the effects of enemy countermeasures, thereby permitting radar echoes to be visible on the indicator.

ANTITRANSMIT-RECEIVE TUBE (ATR).—Tube that isolates the transmitter from the antenna and receiver. Used in conjunction with a TR tube.

ARITHMETIC LOGIC UNIT (ALU).—Generally, a part of the central processing unit in computers and microprocessors.

ARITHMETIC.—Related to the four operations of addition, subtraction, multiplication, and division.

ARTIFICIAL TRANSMISSION LINE.—An LC network that is designed to simulate characteristics of a transmission line.

ASYNCHRONOUS.—Having no fixed time relationship.

AUGEND.—In addition, the number to which the addend is added.

AUTOMATIC GAIN CONTROL (AGC).—A control circuit to automatically change receiver gain so that output signals remain relatively constant with variations in input signal strength.

AVERAGE POWER.—Output power of a transmitter as measured from the start of one pulse to the start of the next pulse.

AXIS.—A straight line, either real or imaginary, passing through a body around which the body revolves.

AZIMUTH.—Angular measurement in the horizontal plane in a clockwise direction.

BALANCED MIXER.—Waveguide arrangement that resembles a T and uses crystals for coupling the output to a balanced transformer.

BANDWIDTH.—The range of frequencies an amplifier can amplify without causing unacceptable distortion to the input signal.

BEARING RESOLUTION.—Ability of a radar to distinguish between targets that are close together in bearing.

BEAT FREQUENCIES.—Difference and sum frequencies that result from combining two different frequencies.

BENCH MARK.—A permanent reference target established by surveying. Its position, with respect to an equipment, is recorded in the smooth log, enabling the shipyard and ship force personnel to check alignment or adjust transmitting components at future dates without repeating the complete alignment procedure.

BINARY.—Having two values or states. The binary number system has two digits.

BIT.—Binary digit. A 1 or a 0.

BLANKING.—The cutting off of the electronic beam in a cathode-ray tube during the time when the picture is not being formed. The beam is blanked while the spot is returning to the starting position (normally right to left).

BLOCKING.—A condition in an amplifier, caused by overdriving one or more stages, in which the amplifier is insensitive to small signals immediately after reception of a large signal.

BORESIGHT TELESCOPE.—An optical instrument mounted in a gun bore or on an equipment for alignment purposes. The optical axis of the boresight represents the pointing line of a gun mount or other equipment.

BROADSIDE ARRAY.—An antenna array in which the direction of maximum radiation is perpendicular to the plane of the array.

BUFFER AMPLIFIER STAGE.—Amplifier stage that isolates one circuit from another. Also called an isolation amplifier.

BURN-THROUGH RANGE.—The distance at which a specific radar can discern targets through the external interference being received. (The interference is normally associated with jamming.)

BYTE.—A binary character string operated upon as a unit and usually shorter than a computer word. Frequently connotes a group of eight bits.

CARRIER FREQUENCY.—The frequency of an unmodulated transmitter output.

CASCADE.—A configuration in which one device drives another.

CELL.—A single storage element in a memory.

CENTERLINE REFERENCE PLANE (CRP).—The plane that contains the ship's centerline and is perpendicular to the master reference plane. This plane is used as the reference for establishing train zero for all equipment aboard ship.

CHAFF.—An airborne cloud of lightweight reflecting objects typically consisting of strips of aluminum foil or metallic coated fibers, which produce clutter echoes in a region of space.

CHARACTER.—A symbol, letter, or numeral.

CIRCUIT.—A combination of electrical and/or electronic components connected together to perform a specified function.

CLEAR.—To reset, as in the case of a flip-flop, counter, or register.

CLINOMETER.—A precision instrument used for measuring equipment roller path inclination. Normally in the custody of support activities. (Also called a gunner's quadrant.)

CLOCK.—The basic timing signal in a digital system.

CLUTTER.—Confusing, unwanted echoes that interfere with the observation of desired signals on a radar indicator.

CODE CONVERTER.—An electronic digital circuit that converts one type of coded information into another coded form.

CODE.—A combination of binary digits that represents information such as numbers, letters, and other symbols.

COHERENT VIDEO.—Bipolar video obtained from a synchonous (coherent) detector.

COHERENCE.—A definite phase relationship between two energy waves, such as transmitted frequency and reference frequency.

COHERENT OSCILLATOR.—In cw radar, this oscillator supplies phase references to provide coherent video from target returns.

COLLIMATION.—The technique of bringing two optical or radio frequency (rf) axes (or a combination of optical and rf axes) into parallelism, including both the measurement and correction of errors. An example of rf-to-optical collimation is the alignment procedure for the tracking axis of a telescope mounted on the director. Collimation of two telescopes is making their optical axes parallel by sighting the projected reticle of one telescope with the other telescope when both are focused at infinity.

COMBAT SYSTEM ALIGNMENT.—Procedures necessary to establish parallelism between combat system equipment axes when the angles defined by their position transmitting components are equal. In the shipyard, combat system alignment is achieved by leveling each equipment to the weapon control reference plane and aligning each equipment to the alignment reference.

COMBINATIONAL LOGIC.—A combination of gate networks, having no storage capability, used to generate a specified function. Sometimes called combinatorial logic.

COMPARATOR.—A device that compares the magnitudes of two quantities and produces an output indicating the relationship of quantities.

COMPLEMENT.—In Boolean algebra, the inverse function. The complement of a 1 is a 0, and vice versa.

CONICAL SCANNING.—Scanning in which the movement of the beam describes a cone, the axis of which coincides with that of the reflector.

CONTACT.—In radar, an object that reflects rf energy (target).

CONTROL DIFFERENTIAL TRANSMITTER (CDX).—A type of synchro that transmits angular information equal to the algebraic sum or difference of the electrical input supplied to its stator, and the mechanical input supplied to its rotor. The output is an electrical voltage taken from the rotor windings.

CONTROL SYNCHRO SYSTEMS.—Synchro systems that contain control synchros and are used to control large amounts of power with a high degree of accuracy. The electrical outputs of these systems control servo systems, which, in turn, generate the required power to move heavy loads.

CONTROL SYSTEM.—A group of components systematically organized to perform a specific control purpose. These systems are categorized as either closed- or open-loop systems. The main difference between the two systems is that the closed-loop system contains some form of feedback.

CONTROL TRANSFORMER (CT).—A type of synchro that compares two signals: the electrical signal applied to its stator and the mechanical signal applied to its rotor. The output is an electrical voltage, which is taken from the rotor winding and is used to control a power amplifying device. The phase and amplitude of the output voltage depends on the angular position of the rotor with respect to the magnetic field of the stator.

CONTROL TRANSMITTER (CX).—A type of synchro that converts a mechanical input, which is the angular position of its rotor, into an electrical output signal. The output is taken from the stator windings and is used to drive either a CDX or CT.

CORE.—A magnetic memory element.

CORNER REFLECTOR.—Two flat reflectors that meet at an angle and are normally fed by a half-wave radiator.

CORRESPONDENCE.—The term given to the positions of the rotors of a synchro transmitter and a synchro receiver when both rotors are on 0° or displaced from 0° by the same angle.

COUNTER.—A digital circuit capable of counting electronic events, such as pulses, by progressing through a sequence of binary states.

CPU.—Central processing unit, a main component in computers.

CROSSED-FIELD TUBE.—High-power electron tube that converts dc to microwave power by a combination of crossed electric and magnetic fields. May be constructed to generate or amplify an rf signal.

CYLINDRICAL PARABOLIC REFLECTOR.—A parabolically shaped reflector that resembles part of a cylinder.

DAMPING.—A mechanical or electrical technique used in synchro receivers to prevent the rotor from oscillating or spinning. Damping is also used in servo systems to minimize overshoot of the load.

D/A CONVERSION.—A process whereby information in digital form is converted into analog form.

DATA TRANSMISSION.—The transfer of information from one place to another or from one part of a system to another.

DATA TRANSMISSION ALIGNMENT.—Procedures necessary to ensure that all components that transmit or receive system quantities are aligned within tolerance.

DATA.—Information in numeric, alphabetic, or other forms.

DECADE COUNTER.—A digital counter having 10 states.

DECODE.—To determine the meaning of coded information.

DECODER.—A digital circuit that converts coded information into a familiar form.

DECREMENT.—To decrease the contents of a register or counter by one.

DEFLECTION COILS.—In a cathode-ray tube, coils used to bend an electron beam a desired amount.

DEIONIZATION TIME.—In a spark gap, the time required for ionized gas to return to its neutral state after the spark is removed.

DELAY.—The time interval between the occurrence of an event at one point in a circuit and the corresponding occurrence of a related event at another point.

DEMODULATOR.—A circuit used in servo systems to convert an ac signal to a dc signal. The magnitude of the dc output is determined by the magnitude of the ac input signal, and its polarity is determined by whether the ac input signal is in or out of phase with the ac reference voltage.

DESIGNATION.—Operational phase of a fire control or track radar during which the radar is directed to the general direction of a desired target.

DIFFERENCE.—The result of a subtraction.

DIGIT.—A symbol representing a given quantity in a number system.

DIGITAL.—Related to digits or discrete quantities.

DIODE DETECTOR.—A demodulator that uses one or more diodes to provide a rectified output with an average value that is proportional to the original modulation.

DIP ANGLE.—$D = 0.98 \times h$ where $h$ is expressed in feet above the centerline and $D$ is given in minutes of arc.

DIRECTIONAL ANTENNA.—An antenna that radiates most effectively in only one direction.

DIRECTIVITY.—Ability of an antenna to radiate or receive more energy in some directions than in others. The degree of sharpness of the antenna beam.

DISCRIMINATOR.—A circuit in which amplitude variations are derived in response to phase or frequency variations.

DISTILLED WATER.—Water that has been purified through a process of evaporation and condensation.

DIVIDEND.—In a division operation, the quantity that is being divided.

DIVISOR.—In a division operation, the quantity that is divided into the dividend.

DMA.—Direct memory access.

DOPPLER EFFECT.—In radar, the change in frequency of a received signal caused by the relative motion between the radar and the target.

DOPPLER FREQUENCY.—Difference between transmitted and reflected frequencies caused by the Doppler effect.

DOWN COUNT.—A counter sequence in which each successive state is less than the previous state in binary value.

DRY-AIR SYSTEM.—Provides dehumidified air for electronic equipment that is moisture critical.

DUCTING.—Trapping of an rf wave between two layers of the Earth's atmosphere or between an atmospheric layer and the Earth.

DUPLEXER.—A radar device that switches the antenna from the transmitter to the receiver and vice versa.

DUPLEX.—Bidirectional transmission of data along a transmission line.

DUTY CYCLE.—In a transmitter, ratio of time on to time off.

E-TRANSFORMER.—A special form of differential transformer employing an E-shaped core. The secondaries of the transformer are wound on the outer legs of the E, and the primary is on the center leg. An output voltage is developed across the secondary coils when its armature is displaced from its neutral position. This device is used as an error detector in servo systems that have limited load movements.

ECHO.—The rf signal reflected back from a radar target.

ELECTROMAGNETIC COMPATIBILITY (EMC).—The capability of electronic equipment and systems to operate in the intended environment at designated levels of efficiency without degradation due to unintentional interference.

ELECTROMAGNETIC INTERFERENCE (EMI).—Impairment of the reception of a wanted electromagnetic signal caused by an electromagnetic disturbance, either intentional or unintentional.

ELECTRONIC COUNTER-COUNTERMEASURES (ECCM).—That division of electronic warfare involving actions taken to ensure friendly effective use of the electromagnetic spectrum despite the enemy's use of electronic warfare.

ELECTRONIC COUNTERMEASURES (ECM).—That division of electronic warfare involving actions taken to prevent or reduce an enemy's effective use of the electromagnetic spectrum.

ELECTRONIC WARFARE (EW).—Action involving the use of electromagnetic energy to determine, exploit, reduce, or prevent hostile use of the electromagnetic spectrum, and action that retains friendly use of the electromagnetic spectrum. There are three divisions within electronic warfare: electronic warfare support measures, electronic countermeasures, and electronic counter-countermeasures.

ELECTRONIC WARFARE SUPPORT MEASURES (ESM).—That division of electronic warfare involving actions taken to search for, intercept, locate, and identify immediately radiated electromagnetic energy for the purpose of immediate threat recognition.

ELECTRONIC COUNTER-COUNTERMEASURES (ECCM) CIRCUITS.—See antijamming circuit.

ELECTRONIC FREQUENCY COUNTER.—An instrument that counts the number of cycles (pulses) occurring during a precise time interval.

ELECTRONIC SCANNING.—Scanning in which the axis of the beam is moved, relative to the antenna axis, in a desired pattern.

ELECTRONICS DRY-AIR BRANCH.—A common line for providing dry air to various electronic equipment, such as search radar, fire control radar, and repeaters.

ELEVATION ANGLE.—The angle between the horizontal plane and the line sight.

ELEVATION ZERO.—Elevation position at which the boresight axis and the elevation trunnion are parallel to the equipment roller path plane within prescribed tolerances.

EMERGENCY POWER.—Temporary source of limited electrical power used upon the loss of the normal power source.

EMISSION CONTROL (EMCON).—(1) The management of electromagnetic radiations to counter an enemy's capability to detect, identify, or locate friendly emitters for exploitation by hostile action. (2) Controlling the radiation of an active system, such as a radar, so that it emits energy only when absolutely necessary to perform its mission.

ENABLE.—To activate or put into an operational mode.

ENCODE.—To convert information into coded form.

END-AROUND CARRY.—The final carry that is added to the result in a 1's or 9's complement addition.

ERROR DETECTOR.—The component in a servo system that determines when the load has deviated from its ordered position, velocity, and so forth.

ERROR REDUCER.—The name commonly given to the servomotor in a servo system. So named because it reduces the error signal by providing feedback to the error detector.

ERROR SIGNAL.—The signal whose amplitude and polarity or phase are used to correct the alignment between the controlling and the controlled element. It is also the name given to the electrical output of a control transformer (CT).

ERROR CORRECTION.—The process of correcting bit errors occurring in a digital code.

ERROR DETECTION.—The process of detecting bit errors occurring in a digital code.

EVEN PARITY.—A characteristics of a group of bits having an even number of 1s.

EXCITATION VOLTAGE.—The supply voltage required to excite a circuit.

EXCLUSIVE-OR.—A logic function that is true if one but not both of the variables is true.

EXECUTE.—The cycle of a CPU in which an instruction is carried out.

FALL TIME.—The time interval between the 90-percent point to the 10-percent point on the negative-going edge of a pulse.

FAST-TIME-CONSTANT (FTC) CIRCUIT.—Differentiator circuit in the first video amplifier that allows only the leading edges of target returns, no matter how small or large.

FEEDBACK.—The return of a portion of the output of a circuit to its input.

FEEDHORN.—A horn radiator used to feed a reflector.

FETCH.—The cycle of a CPU in which an instruction or data byte is retrieved from the memory.

FIRST DETECTOR.—See mixer.

FIXED POINT.—A binary point having a fixed location in a binary number.

FLIP-FLOP.—A bistable device used for storing a bit of information.

FLOATING POINT.—A binary point having a variable location in a binary number.

FORACS.—Fleet Operational Readiness Accuracy Check Site.

FREQUENCY AGILITY.—This term refers to a radar's ability to change frequency within its operating band. Pulse-to-pulse frequency shift or changing the transmitter frequency radically during every interpulse is the ultimate in frequency agility.

FREQUENCY DIVERSITY.—Method of transmission and/or reception using a number of frequencies simultaneously to minimize the effects of selective fading, deliberate jamming, or interference.

FREQUENCY SCANNING.—Varying the output frequency to achieve electronic scanning.

FREQUENCY SPECTRUM.—In a radar, the entire range of frequencies contained in an rf pulse or signal.

FREQUENCY SYNTHESIZER.—A bank of oscillators in which the outputs can be mixed in various combinations to produce a wide range of frequencies.

FREQUENCY RESPONSE.—The measure of a servo's ability to respond to various input frequencies.

FREQUENCY.—The number of pulses in 1 second for a periodic waveform. Expressed in hertz (Hz) or pulses per second (pps).

FULL ADDER.—A digital circuit that adds two binary digits and an input carry to produce a sum and an output carry.

FULL-DUPLEX.—Simultaneous bidirectional transmission of data on a transmission line.

GAIN.—Any increase in the strength of a signal.

GATE.—A logic circuit that performs a specified logical operation such as AND, OR, NAND, NOR, and Exclusive-OR.

GATED AGC.—Circuit that permits automatic gain control to function only during short time intervals.

GENERATOR.—An energy source for producing electrical or magnetic signals.

GLITCH.—A voltage or current spike of short duration and usually unwanted.

GLOW DISCHARGE.—Discharge of electricity through a gas in an electron tube.

GROUND CLUTTER.—Unwanted echoes from surrounding land masses that appear on a radar indicator.

GROUND RANGE.—The distance on the surface of the Earth between a radar and its target. Equal to slant range only if both radar and target are at the same altitude.

GUIDANCE RADAR.—System that provides information that is used to guide a missile to a target.

GYRO.—Abbreviation for gyroscope.

GYROSCOPE.—A mechanical device containing a spinning mass mounted so that it can assume any position in space.

HALF ADDER.—A digital circuit that adds 2 bits and produces a sum and an output carry. It cannot handle input carries.

HALF-POWER POINT.—A point on a waveform or radar beam that corresponds to half the power of the maximum power point (3 dB).

HARD-TUBE MODULATOR.—A high-vacuum electron tube modulator that uses a driver for pulse forming.

HEIGHT-FINDING RADAR.—Radar that provides target altitude, range, and bearing data.

HEXADECIMAL.—A number system consisting of 16 characters. A number system with a base of 16.

HITS PER SCAN.—The number of times an rf beam strikes a target per antenna revolution.

HORIZONTAL PLANE.—Imaginary plane that is tangent (or parallel) to the Earth's surface at a given location.

HORIZON CHECK.—Procedures used to evaluate elevation zero alignment and roller path inclination. This procedure is normally performed while the ship is at sea.

HORIZONTAL.—A line or plane that is normal to the vertical.

HORN ANTENNA.—See horn radiator.

HORN RADIATOR.—A tubular or rectangular microwave antenna that is tapered and is wide at the open end.

HYBRID RING.—A circular waveguide arrangement with four branches. When properly terminated, energy is transferred from any one branch into any two of the remaining three branches.

HYBRID MIXER.—See balanced mixer.

IF AMPLIFIER.—Usually a narrow-bandwidth IF amplifier that is tuned to one of the output frequencies produced by the mixer.

INCREMENT.—To increase the contents of a register or counter by 1.

INDEX OF REFRACTION.—The degree of bending of an rf wave when passing from one medium to another.

INDEX REGISTER.—A register used for indexed addressing in a microprocessor.

INDEXING.—The modification of the address of the operand contained in the instruction of a microprocessor.

INDICATOR.—Equipment that provides a visual presentation of target position information.

INDIRECT ADDRESS.—The address of the address of an operand.

INERTIA.—The physical tendency of a body in motion to remain in motion and a body at rest to remain at rest unless acted upon by an outside force (Newton's first law of motion).

INFORMATION.—In a digital system, the data as represented in binary form.

INITIALIZE.—To put a logic circuit in a beginning state, such as to clear a register.

INSTANTANEOUS AUTOMATIC GAIN CONTROL (IAGC).—Circuit that can vary the gain of the radar receiver with each input pulse to maintain the output peak amplitude nearly constant.

INSTRUCTION.—In a microprocessor or digital computer system, the information that tells the machine what to do. One step in a computer program.

INTERMEDIATE FREQUENCY (IF).—A lower frequency to which an rf echo is converted for ease of amplification.

INTERRUPT.—The process of stopping the normal execution of a program in a computer in order to handle a higher priority task.

INTERSUBSYSTEM.—Relationship between two or more subsystems.

INTRASUBSYSTEM.—Relationship within a subsystem or between the equipments of a subsystem.

INVERSION.—Conversion of a HIGH level to a LOW level or vice versa.

INVERTER.—The digital circuit that performs inversion.

J-K FLIP-FLOP.—A type of flip-flop that can operate in the set, reset, no change, and toggle modes.

JITTERED PRF.—The PRF is rapidly varied at a random rate so that false targets appear to jitter or appear fuzzy on the scope. An alternative to jittered PRF is to change the PRF momentarily. This causes the false targets to change their position on the scope.

JUMP.—A computer operation in which a computer goes from one point in a program to another point or to another program by skipping the normal sequence of instructions. A type of microprocessor instruction.

KEEP-ALIVE VOLTAGE.—Dc voltage applied to a TR gap electrode to produce a glow discharge that allows the tube to ionize faster when the transmitter fires.

KEYED-OSCILLATOR TRANSMITTER.—A transmitter in which one stage is used to produce the rf pulse.

KLYSTRON POWER AMPLIFIER.—Multicavity microwave electron tube that uses velocity modulation.

LIN-LOG AMPLIFIER.—Amplifier in which the response is linear for weak signals and logarithmic for large signals.

LINE OF SIGHT.—Straight line from a radar antenna to a target.

LINE-PULSING MODULATOR.—Circuit that stores energy and forms pulses in the same circuit element, usually the pulse-forming network (pfn).

LIQUID-COOLING SYSTEM.—Source of cooling for high-heat producing equipments, such as microwave components, radar repeaters, and transmitters.

LOBE.—An area of greater signal strength in the transmission pattern of an antenna.

LOGARITHMIC RECEIVER.—Receiver that uses a linear logarithmic amplifier (lin-log) instead of a normal linear amplifier.

LOW-NOISE AMPLIFIER.—See preamplifier.

MAGIC T.—See balanced mixer.

MAGNETRON OSCILLATOR.—Crossed-field electron tube that provides a high-power output. Theory of operation is based on interaction of electrons with the crossed electric and magnetic fields in a resonant cavity.

MAGNETIC AMPLIFIER.—An electromagnetic device that uses one or more saturable reactors to obtain a large power gain. This device is used in servo systems requiring large amounts of power to move heavy loads.

MAINTENANCE DATA SUBSYSTEM (MDS).—Provides a means of recording alignments that are performed under the PMS.

MASTER OSCILLATOR.—In a transmitter, the oscillator that establishes the carrier frequency of the output.

MASTER REFERENCE PLANE (MRP).—The foundation machining reference and the roller path inclination reference during initial construction.

MECHANICAL SCANNING.—The reflector, its feed source, or the entire antenna is moved in a desired pattern.

MINIMUM DISCERNIBLE SIGNAL (MDS).—The weakest signal that produces a usable signal at the output of a receiver. The weaker the signal, the more sensitive the receiver.

MIXER.—In radar, a circuit that combines the receive rf signal with a local-oscillator signal to effectively convert the received signal to a lower IF frequency signal.

MODE SHIFTING.—In a magnetron, shifting from one mode to another during a pulse.

MODE SKIPPING.—Rather than firing on each successive pulse as desired, the magnetron fires randomly.

MODES.—Operational phases (of a radar).

MODULATOR SWITCHING DEVICE.—Controls the on (discharge) and off (charge) time of the modulator.

MODULATOR.—A circuit used in servo systems to convert a dc signal to an ac signal. The output ac signal is a sine wave at the frequency of the ac reference voltage. The amplitude of the output is directly related to the amplitude of the dc input. The circuit's function is opposite to that of a DEMODULATOR.

MONOPULSE (SIMULTANEOUS) LOBING.—Radar receiving method using two or more (usually four) partially overlapping lobes. Sum and difference channels locate the target with respect to the axis of the antenna.

MONOPULSE RECEIVER.—See monopulse lobing.

MOVING TARGET INDICATOR (MTI).—A device that limits the display of radar information to moving targets.

MULTILOOP SERVO SYSTEM.—Systems that contains more than one servo loop; each loop is designed to perform its own function.

MULTIPLEX.—To put information from several sources onto a single line or transmission path.

MULTIPLEXER.—A digital circuit capable of multiplexing digital data.

MULTIPLICAND.—The number being multiplied.

MULTIPLIER.—The number used to multiply the multiplicand.

MULTISPEED SYNCHRO SYSTEMS.—Systems that transmit data at different transmission speeds; for example, dual-speed and trispeed synchro systems.

NAND GATE.—A logic gate that performs an inverted AND operation (NOT-AND).

NAUTICAL MILE.—The length of a minute of arc of a great circle of the earth (6,076 ft.).

NEGATIVE LOGIC.—The system of logic where a LOW represents a 1 and a HIGH represents a 0.

NEWTON'S SECOND LAW OF MOTION.—If an unbalanced outside force acts on a body, the resulting acceleration is directly proportional to the magnitude of the force, is in the direction of the force, and is inversely proportional to the mass of the body.

NOISE FIGURE.—The ratio of output noise to input noise in a receiver.

NOISE.—In radar, erratic or random deflection or intensity of the indicator sweep that tends to mask small echo signals.

NONREFERENCE EQUIPMENT.—An equipment to which no other equipment is aligned. These equipments are aligned to the alignment reference.

NOR GATE.—A logic gate that performs an inverted OR operation (NOT-OR).

NOT CIRCUIT.—An inverter.

NUMERIC.—Related to numbers.

NUTATING.—Moving an antenna feed point in a conical pattern so that the polarization of the beam does not change.

OCTAL.—A number system having a base of 8, consisting of eight digits.

ODD PARITY.—Referring to a group of binary digits having an odd number of 1s.

OMNIDIRECTIONAL ANTENNA.—An antenna that radiates equally in all directions (nondirectional).

OP CODE.—Operation code. The part of a computer instruction that designates the task to be performed.

OPERAND.—A quantity being operated on in a computer.

OR GATE.—A logic gate that produces a HIGH output when any one or more of its inputs are HIGH.

OSCILLATOR.—An electronic circuit that switches back and forth between two states. The stable multivibrator is an example.

PARABOLIC REFLECTOR.—An antenna reflector in the shape of a parabola. It converts spherical wavefronts from the radiating element into plane wavefronts.

PARALLEL-CONNECTED DUPLEXER.—Configuration in which the TR spark gap is connected across the two legs of the transmission line one-quarter wavelength from the T-junction.

PARITY.—Referring to the oddness or evenness of the number of 1s in a specified group of bits.

PEAK POWER.—Maximum power of the rf pulse from a radar transmitter.

PERIOD.—The time required for a periodic waveform to repeat itself.

PERIODIC.—Repeating at fixed intervals.

PERSISTANCE.—The length of time a phosphor dot glows on a crt before disappearing.

PIP (BLIP).—On a CRT display, a spot of light or a base-line irregularity representing the radar echo.

PLANE WAVEFRONTS.—Waves of energy that are flat, parallel planes and perpendicular to the direction of propagation.

PLANNED-POSITION INDICATOR (PPI).—A radar display in which range is indicated by the distance of a bright spot or pip from the center of the screen, and the bearing is indicated by the radial angle of the spot.

PLANNED MAINTENANCE SYSTEM (PMS).—A concept of maintenance that provides availability of equipment for mission support, reliability of equipment without compromise of schedule or quality, full service life at minimum cost, maximum utilization of skilled personnel, and control for quick reaction to changes.

POINTING LINE.—The line of sight, boresight, or rf axis that defines the direction in which an equipment is pointed.

POSITION SENSOR.—A component in a servo system that measures position and converts the measurement into a form convenient for transmission as a feedback signal.

POSITION SERVO SYSTEM.—A servo system whose end function is to control the position of the load it is driving.

POSITIVE LOGIC.—The system of logic where a HIGH represents a 1 and a LOW represents a 0.

POTENTIOMETER.—An electromechanical device, used as a position sensor, having a terminal connected to each end of a restrictive element, and a third connected to a wiper contact. The output is a voltage that is variable, depending upon the position of the wiper contact. The potentiometer is commonly referred to as a variable voltage divider. It, in effect, converts mechanical information into an electrical signal.

POWER GAIN.—In an antenna, the ratio of its radiated power to that of a reference.

POWER-AMPLIFIER (CHAIN) TRANSMITTER.—Transmitter that uses a series of power amplifiers to create a high level of power.

PREAMPLIFIER (PREAMP).—An amplifier that raises the output of a low-level source for further processing without appreciable degradation of the signal-to-noise ratio.

PRESET.—To initialize a digital circuit to a predetermined state.

PRIMARY LOOP.—In a cooling system, the primary source of cooling for the distilled water.

PRIORITY ENCODER.—A digital logic circuit that produces a coded output corresponding to the highest valued input.

PROBE COUPLER.—A resonant conductor placed in a waveguide or cavity to insert or extract energy.

PRODUCT.—The result of a multiplication.

PRODUCT-OF-SUMS.—A form of Boolean expression that is the ANDing of ORed terms.

PROGRAM.—A list of instructions that are arranged in a specified order to control the operation of a microprocessor system or computer. The program tells the machine what to do on a step-by-step basis.

PROGRAM COUNTER.—A counter in a microprocessor that keeps up with the place in the program. It acts as a "bookmark" that tells the computer the next instruction to be executed.

PULSE WIDTH.—Duration of time between the leading and trailing edges of a pulse (pulsewidth for radar).

PULSE.—A sudden change from one level to another followed by a sudden change back to the original level.

PULSE-FORMING NETWORK (PFN).—An LC network that alternately stores and releases energy in an approximately rectangular wave.

PULSE-REPETITION RATE (PRR).—Average number of pulses per unit of time; pulse rate.

PULSE-REPETITION FREQUENCY (PRF).—The rate at which pulses are transmitted, given in hertz or pulse per second; reciprocal of pulse-repetition time.

PULSE-REPETITION TIME (PRT).—Interval between the start of one pulse and the start of the next pulse; reciprocal of pulse-repetition frequency.

PULSES PER SECOND (pps).—A measure of frequency of a pulse waveform.

QUOTIENT.—The result of a division.

RADAR ABSORBENT MATERIAL (RAM).—Radar absorbent material used as a radar camouflage device to reduce the echo area of an object.

RADAR BEAM.—The space in front of a radar antenna where a target can be effectively detected or tracked.

RADAR DISTRIBUTION SWITCHBOARD.—An electrical switching panel used to connect inputs from any of several radars to repeaters.

RADAR TEST SET.—Combination of several test circuits and equipment used to test various characteristics of a radar.

RADAR.—Derived from RAdio Detecting And Ranging.

RADIX.—The base of a number system. The number of digits in a given number system.

RAM.—Random access memory. Also, see radar absorbent material.

RANGE MARKER.—A movable vertical pulse on a A-scope or ring on a PPI scope used to measure the range of an echo or to calibrate the range scale.

RANGE RESOLUTION.—Ability of a radar to distinguish between targets that are close together in range.

RANGE STEP.—On an A-scope sweep, vertical displacement used to measure the range of an echo.

RANGE.—The length of a straight line between a radar and a target.

RANGE-HEIGHT INDICATOR (RHI).—A radar display on which slant range is shown along the X axis and height along the Y axis.

RANGE-GATE.—A movable gate used to select radar echoes from a very short-range interval.

RATE GYRO.—A gyro used to detect and measure angular rates of change.

READ.—The process of retrieving information from a memory.

RECEIVER SENSITIVITY.—The degree to which a receiver can usefully detect a weak signal; the lower limit of useful signal input to the receiver.

RECEIVER.—In radar, a unit that converts rf echoes to video and/or audio signals.

RECIRCULATE.—The process of retaining information in a register as it is shifted out.

RECOVERY TIME.—In a radar, the time interval between the end of the transmitted pulse and the time when echo signals are no longer attenuated by the TR gap.

REFERENCE MARK.—A permanent marker installed during ship construction to identify the ship's centerline, offset centerline, or equipment bench marks.

REFLECTING OBJECT.—In radar, an air or surface contact that provides an echo.

REFLEX KLYSTRON.—A microwave oscillator that is tuned by changing the repeller voltage.

REFRACTION.—The bending of rf waves as the waves pass through mediums of different density.

REFRACTIVE INDEX.—In a wave-transmission medium, the ratio between the phase velocity in free space and in the medium.

REGISTER.—A digital circuit capable of storing and moving (shifting) binary information. Typically used as a temporary storage device.

RESET.—The state of a flip-flop, register, or counter when 0s are stored. Equivalent to the clear function.

RESOLVER.—A rotary, electromechanical device used to perform trigonometric computations by varying the magnetic couplings between its primary and secondary windings. It is generally used in circuits that solve vector problems, such as analog computers and conversion equipment. The resolver solves three different types of problems:

- Resolution—separating a vector into two mutually perpendicular components.

- Composition—combining two components of a vector to produce a vector sum.

- Combination—the process of resolution and composition taking place simultaneously.

RESULTANT MAGNETIC FIELD.—The magnetic field produced in a synchro by the combined effects of the three stator magnetic fields.

RETURN.—The rf signal reflected back from a radar target (echo).

RF RADIATION HAZARD.—Health hazard caused by exposure to electromagnetic radiation or high-energy particles (ions). Abbreviated RADHAZ.

RIGIDITY.—The tendency of the spin axis of a gyro wheel to remain in a fixed direction in space if no force is applied to it.

RINGING.—RF oscillations caused by excitation of a resonant circuit (cavity).

RISE TIME.—The time required for the positive-going edge of a pulse to go from 10% of its full value to 90% of its full value.

ROTOR.—The rotating member of a synchro that consists of one or more coils of wire wound on a laminated core. Depending on the type of synchro, the rotor functions similar to the primary or secondary winding of a transformer. In a gyro, the rotating member is sometimes called a gyro wheel.

SCALING FACTOR.—The term used to describe the use of unequal resistors in a servo's summing network to compensate for differences between input and output signal levels.

SCANNING.—Systematic movement of a radar beam to cover a definite pattern or area in space.

SCINTILLATION.—Apparent change in target reflectivity. Motion of the target causes radar pulses to bounce off different parts of the target, such as fuselage and wing tip.

SEA CLUTTER.—Unwanted echoes from the irregular surface of the sea that appear on a radar indicator.

SEARCH RADAR SYSTEM.—Early-warning device that searches a fixed volume of space.

SECONDARY LOOP.—In a cooling system, the loop that transfers the heat from the heat source (electronic equipment) to the primary loop usually distilled or demineralized water.

SENSITIVITY TIME CONTROL (STC).—Programmed variation of the gain (sensitivity) of a radar receiver as a function of time within each pulse repetition interval or observation time. Prevents overloading of the receiver by strong echoes from targets or clutter at close ranges. The STC reduces the gain of the radar receiver for detection of close-in targets. It is particularly effective in removing close-in clutter and strong nearby signals. When adjusting STC, particular attention must be paid to close-in ranges so that small reflecting surfaces are not eliminated.

SEQUENTIAL LOGIC.—A broad category of digital circuits whose logic states depend on a specified time sequence.

SERIAL.—An in-line arrangement where one element follows another, such as in a serial shift register. Also, the occurrence of events, such as pulses, in a time sequence rather than simultaneously.

SERVO AMPLIFIER.—Either ac or dc amplifiers used in servo systems to build up signal strength. These amplifiers usually have relatively flat gain versus frequency response, minimum phase shift, low output impedance, and low noise level. The dc amplifier is subject to excessive drift and is relatively unstable. However, the ac amplifier is considered drift free and has a constant dynamic gain over a variety of operating points.

SERVOMOTOR.—An ac or dc motor used in servo systems to move a load to a desired position or at a desired speed. The ac motor is usually used to drive light loads at a constant speed, while the dc motor is used to drive heavy loads at varying speeds.

SERVO SYSTEM.—An automatic feedback control system that compares a required condition (desired value, position, and so forth) with an actual condition and uses the difference to adjust a control device to achieve the required condition.

SET.—The state of a flip-flop when it is in the binary 1 state.

SHIFT REGISTER.—A digital circuit capable of storing and shifting binary data.

SHIFT.—To move binary data within a shift register or other storage device.

SPHERICAL WAVEFRONTS.—Waves of energy that spread out in concentric circles.

SR FLIP-FLOP.—A set-reset flip-flop.

STABILITY.—In a magnetron, the ability to maintain normal operating characteristics.

STAGE.—One storage element in a register or counter.

STATIC MEMORY.—A memory composed of storage elements such as flip-flops or magnetic cores that are capable of retaining information indefinitely.

STATOR.—The stationary member of a synchro that consists of a cylindrical structure of slotted laminations on which three Y-connected coils are wound with their axes 120° apart. Depending on the type of synchro, the stator's functions are similar to the primary or secondary windings of a transformer.

STATUTE MILE.—5,280 ft.

STICKOFF VOLTAGE.—A low voltage used in multispeed synchro systems to prevent false synchronizations.

STORAGE.—The memory capability of a digital device. The process of retaining digital data for later use.

STROBE.—A pulse used to sample the occurrence of an event at a specified point in time in relation to the event.

STUB.—A short section of transmission line connected in parallel with the main transmission line.

SUBROUTINE.—A program that is normally used to perform specialized or repetitive operations during the course of a main program. A subprogram.

SUBTRACTOR.—One of the operands in a subtraction.

SUBTRAHEND.—The other operand in a subtraction.

SUM.—The result of an addition.

SUM-OF-PRODUCTS.—A form of Boolean expression that is the ORing of ANDed terms.

SUMMING NETWORK.—A combination of two or more parallel resistors used in servo systems as error detectors. The output of the network is the algebraic sum of the inputs.

SUPERHETERODYNE RECEIVER.—A type of receiver that uses a mixer to convert the rf echo to an IF signal for amplification.

SUPPORT SYSTEM.—For a radar, a system that provides an auxiliary input, such as dry air, electrical power, or liquid cooling.

SYNCHRONIZER.—Circuit that supplies timing signals to other radar components.

SYNCHRO.—A small motorlike device that operates like a variable transformer and is used primarily for the rapid and accurate transmission of data among equipments and stations.

SYNCHRONOUS.—Having a fixed time relationship.

TACHOMETER.—A small ac or dc generator, sometimes referred to as a rate generator, which converts its shaft speed into an electrical output. The tachometer is frequently used in servo systems to sense the velocity of a load.

TARGET.—In radar, a specific object of radar search or detection.

TARGET RESOLUTION.—The ability of a radar to distinguish between two or more targets that are close to each other.

TERMINAL COUNT.—The final state of a counter sequence.

THEODOLITE.—A precision surveying instrument used for train and elevation zero alignments (more precise than a transit). Normally in the custody of support activities.

THREE-DIMENSIONAL (3-D) RADAR.—Measures the range, bearing, and altitude of a target.

THYRATRON.—Gas tube used as a modulator switching device.

TIME LAG.—The delay in a servo system between the application of the input signal and the actual movement of the load.

TIMER.—See synchronizer.

TOGGLE.—The action of a flip-flop when it changes back and forth between its two states on each clock pulse.

TORQUE.—A measure of how much load a machine can turn. This measurement is expressed either in ounce-inches for torque synchro systems or in pound-feet for heavy machinery.

TORQUE DIFFERENTIAL RECEIVER (TDR).—A type of differential synchro that takes two electrical inputs, one to the rotor and one to the stator, and produces a mechanical output. The output is the angular position of the rotor, which represents the algebraic sum or difference of the two electrical inputs.

TORQUE DIFFERENTIAL SYNCHRO SYSTEM.—A synchro system containing either a TDX or a TDR. This system is used in application where it is necessary to compare two signals, add or subtract the signals, and furnish an output proportional to the sum or difference between the two signals.

TORQUE DIFFERENTIAL TRANSMITTER (TDX).—This type of synchro is functionally the same as the CDX except that it is used in torque systems rather than control systems.

TORQUE GRADIENT.—A term used in the rating of torque synchros. It is expressed in the number of inch-ounces of torque required to pull a specific synchro 1° away from its normal position (0.4 inch-ounce per degree).

TORQUE RECEIVER (TR).—A type of synchro that converts the electrical input supplied to its stator back to a mechanical angular output through the movement of its rotor.

TORQUE SYNCHRO SYSTEM.—A synchro system that uses torque synchros to move light loads such as dials, pointers, and other similar devices.

TORQUE TRANSMITTER (TX).—This type of synchro is functionally the same as the CX except that it is used in torque synchro systems.

TR RECOVERY TIME.—Time required for a fired TR or ATR tube to deionize to a normal level of conductance.

TRACK RADAR.—Radar that provides continuous range, bearing, and elevation data by keeping the rf beam on the target.

TRACK.—Operational phase of a fire control or track radar during which the radar beam is kept on the target.

TRAILING EDGE.—The second transition of a pulse.

TRAIN ZERO.—Train position where the bearing line is normal to the ship centerline and pointing forward.

TRAM BLOCK.—A block and a pin with a cupped end (into which the ends of the tram bar fit). One tram block is permanently fastened to the rotating structure and another to the fixed structure in such a manner that when the ends of the tram bar are in each tram block, the equipment is at the tram position.

TRANSITION.—A change from one level to another.

TRANSIT.—A precision surveying instrument used for train and elevation zero alignments that is normally less precise than a theodolite.

TRANSMIT-RECEIVE TUBE (TR).—Gas-filled rf switch that is used in a duplexer.

TRANSMITTER.—Equipment that generates, amplifies, and modulates electromagnetic energy.

TRANSMITTER FREQUENCY (CARRIER FREQUENCY).—The frequency of the unmodulated output of a transmitter.

TRAVERSE (BEARING) SIGNAL.—In a monopulse radar system, the combination of individual lobe signals that represents target offset direction and amplitude from the antenna axis.

TRIGGER.—A pulse used to initiate a change in the state of a logic circuit.

TRIGGER PULSES.—In radar, pulses that are used to initiate specific events.

TROUBLE INDICATORS.—Signal lights used to aid maintenance personnel in locating synchro troubles quickly.

TROUBLE TABLES.—Tables of trouble symptoms and probable causes furnished by many manufacturers, with their equipment, to help technicians isolate synchro problems.

TRUE BEARING.—Angle between a target and true north measured clockwise in the horizontal plane.

TRUE NORTH.—Geographic north.

TRUNCATED PARABOLOID.—A paraboloid reflector that has been cut away at the top and bottom to increase beamwidth in the vertical plane.

TWO-DIMENSIONAL (2-D) RADAR.—Measures the range and bearing to a target.

UP-COUNT.—A counter sequence in which each binary state has a successively higher value.

VELOCITY SERVO SYSTEM.—A servo system that controls the speed of the load it is driving.

VERTICAL.—A line or plane passing through a point on the surface and the center of the Earth. Vertical is usually established by use of a device, such as a clinometer, that is dependent upon the force of gravity to position a bubble of air in a liquid. Such a device is actually sensing the center of the Earth's gravitational field rather than the physical center of the Earth. For all practical purposes, the ambiguities that may result from disparities between the physical center of the Earth and the center of the Earth's gravitational field are negligible when considered from the aspect of combat system alignment accuracy.

VERTICAL PLANE.—Imaginary plane that is perpendicular to the horizontal plane.

VOLTAGE STANDING WAVE RATIO (VSWR).—In a waveguide, the ratio of the electric field at a maximum point to that of an adjacent minimum point.

WAVEMETER.—An instrument for measuring the wavelength of an rf wave.

WEAPON CONTROL REFERENCE PLANE (WCRP).—The reference plane for leveling all equipment of the ship combat system.

WEIGHT.—The value of a digit in a number based on its position in the number.

WORD.—A group of bits representing a complete piece of digital information.

WRITE.—The process of storing information in a memory.

X-RAY EMISSION.—Penetrating radiation similar to light, but with shorter wavelengths, that can penetrate human tissue.

ZEROING.—The process of adjusting a synchro to its electrical zero position.

# APPENDIX II

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# INDEX

A

Absorption, 6-35
Acceleration servo operation, 1-17
Accumulator (ACC) registers, 3-36
Active status register (ASR), 3-29, 3-35
Adsorption, 6-35
AGC (automatic gain control), 4-66
Air-to-air cooling, 6-2 to 6-3
Air-to-liquid cooling, 6-3 to 6-4
Alignment afloat, 7-1
Alignment concepts, 7-1 to 7-5
Alignment considerations, 7-16 to 7-19
Alignment procedures, 7-19 to 7-30
Alignment sights, 7-10 to 7-12
AM/FM phasing, 8-24
Ambiguities and radar resolution, 4-6
Amplidyne generator, 1-33 to 1-34
Amplidynes, 1-33 to 1-36
AN/UYK-7(V), digital computer set, 3-20 to 3-57
Analog computers, 3-1
Analog computing elements, 2-1 to 2-38
  electrical and electronic computing elements, 2-11 to 2-37
    gain compensating resistor, 2-17 to 2-18
    multiplication and division operations, 2-20 to 2-25
      cascading potentiometers for multiplication, 2-22 to 2-24
      division with potentiometers, 2-24 to 2-25
      double-ended potentiometer as a multiplier, 2-22
      multiplication of two variables with a potentiometer, 2-20 to 2-21
Analog computing elements—Continued
  electrical and electronic computing elements—Continued
    operational amplifiers, 2-35 to 2-37
      logarithmic functions, 2-36 to 2-37
    parallel resistor networks, 2-11 to 2-17
      features provided by negative feedback, 2-14
      scale changing (multiplication and division), 2-14 to 2-17
      sign reversing loop with unity gain, 2-13 to 2-14
      summing amplifier, 2-12 to 2-13
    rate computing loops, 2-35
    servo multiplier, 2-25 to 2-27
    summation operations, 2-18 to 2-20
      basic summing computing loop, 2-18 to 2-19
      summation of voltages with dissimilar scale factors, 2-19 to 2-20
    trigonometric functions, 2-27 to 2-35
      basic resolver loop (practical application), 2-30 to 2-31
      basic resolver operation, 2-27 to 2-30
      composition, 2-32 to 2-34
      inverse sine and cosine loops, 2-34 to 2-35
      resolution, 2-31 to 2-32
  electromechanical computing elements, 2-4 to 2-11
    potentiometers, 2-5 to 2-10
      double-ended potentiometer, 2-8 to 2-9
      multiturn potentiometers, 2-9 to 2-10

Analog computing elements—Continued
  electromechanical computing elements—Continued
    potentiometers—Continued
      representing computing variables electrically, 2-6 to 2-8
      sine and cosine potentiometers, 2-10
      types of potentiometers, 2-5
    rate generators, 2-10 to 2-11
  scale factors, 2-2 to 2-4
    choice of scale factors, 2-3 to 2-4
    scale factors in analog computers, 2-3
    scale factor analysis, 2-4
  summary, 2-37 to 2-38
Analog units, 2-3
Angle error detection, 4-72
Angle of incidence, 5-14
Angle of reflection, 5-14
Angle tracking, 4-13
Angular displacement, 7-5
Antenna beamwidth, 4-10
Antenna factors, 4-10 to 4-11
Antenna gain, 4-10
Antenna loss factor, 4-10
Antennas, 5-46 to 5-56
Antilog amplifier, 2-37
Applegate diagram, 4-57
Asynchronous tuning, 4-41
Atmospheric absorption, 4-7
ATR tube, 5-45
Autocorrelation, 4-70
Automatic frequency control (AFC), 4-55 to 4-56
Average power, 4-9

**B**

b designators, 3-26
Baking in, 4-34
Balanced duplexer, 5-45
Balanced mixer, 4-63
Barker codes, 4-71
Basic radar principles, 4-5 to 4-6
Basic resolver operation, 2-27 to 2-30
Basic summing computing loop, 2-18 to 2-19
Battery alignment, 7-1 to 7-30
  alignment concepts, 7-1 to 7-5
    angular displacement, 7-5
    frame of reference, 7-2 to 7-3
    linear displacement, 7-5
      dynamic parallax, 7-5
      static parallax, 7-5
  alignment considerations, 7-16 to 7-19
    establishment of bench marks and tram reference readings, 7-18 to 7-19
    establishment of parallelism, 7-17 to 7-18
      foundation machining, 7-17 to 7-18
      inclination verification, 7-17
      interequipment leveling, 7-18
    establishment of reference planes, 7-16 to 7-17
      centerline reference plane, 7-17
      master reference plane, 7-16 to 7-17
      ship base plane, 7-16
      weapon control reference plane, 7-17
    performance of train and elevation space alignment (star checks), 7-18
    establishment of train and elevation zero alignment, 7-18
    performance of fire control radar rf-optical alignment, 7-18
  alignment equipment, 7-5 to 7-16
    alignment sights, 7-10 to 7-12
      boresight telescope, 7-11
      self-contained optics, 7-12
    bench marks, 7-15 to 7-16
    clinometers, 7-7 to 7-9
      clinometer mounting and care, 7-9
      graduated drum, 7-8
    dials, 7-16
    gunner's quadrant, 7-9 to 7-10
    levels, 7-10
      Hilger and Watts TB4, 7-10
      sine bar, 7-10
    theodolite, 7-6 to 7-7
    tram bar and tram blocks, 7-12 to 7-15
    transits, 7-6
      leveling screws, 7-6
      transit LOS, 7-6

Battery alignment—Continued
  alignment procedures, 7-19 to 7-30
    bench mark checks, 7-19
    establishment of train zero, 7-22
    roller path inclination correction methods, 7-28 to 7-29
      computer software, 7-28 to 7-29
      electrical roller path tilt corrector, 7-28
      mechanical roller path tilt corrector, 7-28
      modifying a tilt corrector setting, 7-29
    roller path inclination analysis, 7-23 to 7-28
      bearing of the high point, 7-24
      180° polar-coordinate method, 7-26 to 7-28
      plotting RPP data using rectangle-coordinate method, 7-24 to 7-26
    RPP inclination verification, 7-20 to 7-22
    star checks, 7-23
    tram checks, 7-19 to 7-20
    weapons system smooth record, 7-29 to 7-30
  summary, 7-30
Beacon checks, 8-10
Beam current, 4-42
Beam pattern plot, 8-18, 8-19
Beam phasing, 8-24
Beam position summary graph, 8-20
Beamwidth (radar), 4-6
Beating, 4-6
Behavior of electromagnetic waves within a waveguide, 5-12 to 5-15
Bench mark checks, 7-19
Bench marks, 7-15 to 7-16
Bends, twists, and joints, 5-17 to 5-19
Bethe-hole coupler, 5-32
Bidirectional coupler, 5-31 to 5-32
Bifilar winding, 4-54
Body current, 4-42
Booster amplifier, 2-27
Boresight telescope, 7-11
Boresight-to-target position, 8-20
Boundary conditions, 5-9 to 5-10
Breakpoint compare, 3-34
Breakpoint register, 3-34
Buffer control words (BCWs), 3-19
Bunching action, 4-56

C

C register, 3-34
Capture and guidance modulation slopes, 8-24
Capture and guidance beam power density, 8-24
Capture antenna subassembly, 8-8
Capture beam boresight, 8-23
Capture-guidance mode, 8-7
Capacitor restore, 3-54
Cartesian coordinate system, 7-2
Cascading potentiometers for multiplication, 2-22 to 2-24
Cassegrainian antenna, 5-48, 8-7
Catwhiskers, 4-62
Cavity coupling, 5-25
Cavity resonators, 5-22 to 5-25
Cavity tuning, 5-24 to 5-25
Center of rotation, 7-2
Centerline reference plane, 7-17
Central dry-air system, 6-33
Central processor unit (CPU), 3-30 to 3-39
Centrifugal pump, 6-24
CFA, 4-24
CFAR, 4-67
Chain mode, 3-45
Chain priority, 3-47
Chain registers, 3-47
Channel priority circuits, 3-46
Choice of scale factors, 2-3 to 2-4
Choke joint, 5-18
Circular polarization, 4-5
Circular waveguide, 5-2, 5-10 to 5-12, 8-8
Circulation pump, 6-24 to 6-25
Classifications, radar, 4-5
Clinometer mounting and care, 7-9
Clinometers, 7-7 to 7-9
Closed loop system (servo), basic operating principle of a, 1-1 to 1-5
Coarse CT, 1-19, 1-20, 1-21
Coherent oscillator, 4-23
COHO, 4-23
Collector current, 4-42

Collimation, 7-18, 8-1 to 8-27
  collimation procedures, 8-16 to 8-27
    GFCS Mk 68 collimation, 8-20
    TARTAR collimation procedures, 8-18 to 8-20
      CWI axis collimation, 8-19 to 8-20
      track receiver (TR) axis collimation, 8-18
      track transmit (TX) axis collimation, 8-18 to 8-19
    TERRIER collimation procedures, 8-20 to 8-27
      AM/FM phasing, 8-24
      capture and guidance beam power density, 8-24
      capture and guidance modulation slopes, 8-24
      capture beam boresight, 8-23
      doppler track angle sensitivity, 8-26 to 8-27
      doppler track boresight, 8-26
      guidance beam boresight, 8-20 to 8-23
      pulse track angle sensitivity, 8-26
      pulse track boresight, 8-26
  radar collimation requirements, 8-3 to 8-9
    guided missile fire control system (GMFCS) collimation requirements, 8-3 to 8-4
    TERRIER GMFCS collimation requirements, 8-4 to 8-9
  radar collimation shore tower, 8-10 to 8-16
    collimation test equipment, 8-10 to 8-16
      continuous wave acquisition and track (CWAT) transponder, 8-14
      microwave power meter, 8-14 to 8-16
      radar beacon test set AN/TPN-7, 8-16
      range calibration set AN/SPM-6 series and AN/UPM-115, 8-13 to 8-14
      radar test set AN/SPM-9, 8-12 to 8-13
    tower array, 8-10
  summary, 8-27

Combat system alignment test, 9-7
Combat system testing, 9-4 to 9-5
Combat system tests, 9-7
Command address pointer (CAP), 3-40
Command drivers, 3-47
Command enable, 3-12
Comparator, 8-8
Comparison of ac and dc servos, 1-36
Computer registers, 3-7
Conductance, 6-28
Conductivity, 6-28
Conical scanning, 4-13
Console sequence (CSL SEQ), 3-32
Constant false alarm rate, 4-67
Continuous wave acquisition and track (CWAT) transponder, 8-14
Control board, maintenance, 9-3
Control loop, servo, 1-11 to 1-13
Control section, 3-7 to 3-14
Control systems, 1-1 to 1-7
Convection cooling, 6-1 to 6-2
Coolant alarm switchboard, 6-29 to 6-32
Cooling and dry-air systems, 6-1 to 6-47
  cooling system components, 6-9 to 6-32
    circulation pump, 6-24 to 6-25
    coolant alarm switchboard, 6-29 to 6-32
    cooling system maintenance responsibility, 6-32
    demineralizer, 6-25 to 6-29
    expansion tank, 6-12 to 6-13
    flow monitoring devices, 6-21 to 6-24
    flow regulators, 6-18 to 6-21
    heat exchangers, 6-9 to 6-12
    oxygen analyzer, 6-29
    seawater strainers, 6-13 to 6-15
    temperature regulating valves, 6-15 to 6-18
      three-way temperature regulating valve, 6-15 to 6-17
      two-way temperature regulating valve, 6-17 to 6-18
  electronic equipment cooling methods, 6-1 to 6-4
    air-to-air cooling, 6-2 to 6-3
    air-to-liquid cooling, 6-3 to 6-4
    convection cooling, 6-1 to 6-2
    forced-air cooling, 6-2
    liquid cooling, 6-4

Cooling and dry-air systems—Continued
  radar dry-air system, 6-32 to 6-43
    central dry-air system, 6-33
    dry-air systems, 6-33
    dryer components, 6-35 to 6-41
      dehydrator, 6-39 to 6-41
      dust filter, 6-41
      flow limiter, 6-41
      fluid separator and dump trap, 6-36 to 6-37
      pressure regulator, 6-38 to 6-39
      telltale oil filter and dump trap, 6-37 to 6-38
    equipment dry air, 6-34 to 6-35
    moisture monitor, 6-41 to 6-42
    ships air supply, 6-33
    waveguide flooding, 6-42 to 6-43
      clean-up procedure, 6-42 to 6-43
      isolate extent of flooding, 6-42
  types of liquid cooling systems, 6-4 to 6-9
    primary cooling system, 6-4 to 6-8
    secondary cooling system, 6-8
    type I cooling system, 6-8 to 6-9
    type II cooling system, 6-9
    type III cooling system, 6-9
Copper losses, 5-2
Core memory, 3-6, 3-49 to 3-52
COSRO, 4-16, 8-18
Coupling factor, 5-32
Coupling methods, 4-33
Crossed-field amplifier (CFA), 4-34 to 4-36
Crossed-field tubes (M type), 4-24 to 4-36
Crosslevel lock, 8-20
Cutter reject, 8-18
Cw radar, 4-18 to 4-20
CWI axis collimation, 8-19 to 8-20
CWI reference, 8-3
Cycle schedule, 9-2
Cycle time, 3-3, 3-7

D

Data latch, 3-54
Decibels, 4-1 to 4-3
Dehydrator, 6-33, 6-39 to 6-41
Deionization time, 5-44
Demineralizer, 6-25 to 6-29
Demodulators, 1-23 to 1-25
Designator storage word (DSW) register, 3-36
Dessicant, 6-33
Destructive read-out (DRO), 3-21
Detectors, 4-67 to 4-68
Development of waveguides from parallel lines, 5-3 to 5-4
Dew point, 6-41
Diagnostic testing programs, 9-11 to 9-12
Dials, 7-16
Dielectric losses, 5-2
Digital computers, 3-1 to 3-69
  digital computer Mk 152, 3-2 to 3-20
    functional description of computer Mk 152, 3-3 to 3-20
      computer registers, 3-7
      control section, 3-7 to 3-14
      input/output section, 3-14 to 3-20
      memory capacities and special addresses, 3-6 to 3-7
      memory section, 3-14
    physical description, 3-3
  digital computer set AN/UYK-7(V), 3-20 to 3-57
    physical description, 3-21 to 3-24
      operator controls, 3-21 to 3-24
    unit functional description, 3-24 to 3-57
      central processor unit (CPU), 3-30 to 3-39
      core memory, 3-49 to 3-52
      double-density mated film memory, 3-52 to 3-57
      instruction format, 3-26 to 3-30
      I/O adapter (IOA), 3-47 to 3-49
      I/O controller, 3-39 to 3-47
  introduction to digital computers, 3-2
  peripheral equipment, 3-57 to 3-62
    digital data recorder (DDR), 3-59 to 3-60
      data format subsection, 3-59
      input/output subsection, 3-59
      primary control subsection, 3-59
      tape transport control subsection(s), 3-59 to 3-60
      tape transport(s), 3-60
    input/output console, 3-57 to 3-59
      keyboard printer, 3-58
      logic control, 3-57
      serializer, 3-58 to 3-59
      tape punch, 3-57 to 3-58
      tape reader, 3-58

Digital computers—Continued
    peripheral equipment—Continued
        motor/generator (MG) set, 3-60 to 3-62
            exciter, 3-61
            generator, 3-61
            motor, 3-61
            motor control, 3-61
            voltage regulator, 3-62
        signal data converter (SDC), 3-60
    summary, 3-62
Digital data recorder (DDR), 3-59 to 3-60
Digital matched filter, 4-72
Diode detector, 4-67
Dip difference, 7-20, 7-22, 7-25
Directional couplers, 5-30 to 5-43
Directivity, 5-32, 5-46
Displays, radar, 4-74
Division with potentiometers, 2-24 to 2-25
Doppler, 4-18 to 4-19
Doppler frequency, 4-18
Doppler shift, 4-5, 4-18
Doppler target, 8-26
Doppler track angle sensitivity, 8-26 to 8-27
Doppler track boresight, 8-26
Double-density mated film memory, 3-52 to 3-57
Double-ended potentiometer, 2-8 to 2-9
Double-ended potentiometer as a multiplier, 2-22
Drift tube, 4-35, 4-37
Dryer components, 6-35 to 6-41
Dry-air systems, 6-33
DSOT, 9-7
Ducting, 4-7
Duplexers, 5-43 to 5-45
Dust filter, 6-41
Duty cycle, 4-10
Dynamic parallax, 7-5

E

Effect of a waveguide on different frequencies, 5-4 to 5-5
Electric field, the, 5-6 to 5-8
Electric servo, 1-8
Electrical and electronic computing elements, 2-11 to 2-37
Electrohydraulic servo, 1-9 to 1-13
Electrolysis, 6-11
Electromagnetic fields in a waveguide, 5-5 to 5-10
Electromechanical computing elements, 2-4 to 2-11
Electromechanical servo, 1-8 to 1-9
Electron resonance, 4-27
Electron tube servo amplifier, 1-26 to 1-28
Electronic counter-countermeasures (ECCM), 4-77 to 4-80
Electronic countermeasures (ECM), 4-76 to 4-78
Electronic scanning, 4-15 to 4-18
Electronic warfare, 4-74 to 4-80, 4-82
Elliptical polarization, 4-5
EMC, 4-74
EMI, 4-74
Enable real-time clock monitor, 3-11
Equation units, 2-3
Equipment dry air, 6-34 to 6-35
Equipment level testing, 9-5
Error reducer, 1-3, 1-7, 1-14, 1-37
Error-rate damping, 1-40 to 1-41
Establishment of bench marks and tram reference readings, 7-18 to 7-19
Establishment of reference planes, 7-16 to 7-17
Establishment of train and elevation zero alignment, 7-18
Establishment of train zero, 7-22
Ethylene glycol, 4-46, 6-4
Exciter, 3-61
Expansion tank, 6-12 to 6-13
External interrupt functions, 3-45

F

False alarm probability, 4-8
Faraday rotation, 5-36 to 5-38
Fault isolation, 9-5 to 9-29
Features provided by negative feedback, 2-14
Ferrite attenuator, 5-35
Ferrite isolator, 5-38
Ferrites, 5-33 to 5-34
Final power amplifier (FPA), 5-55
Fine CT, 1-19 to 1-20
Floodlights, 8-10
Flow limiter, 6-41
Flow monitoring devices, 6-21 to 6-24
Flow regulators, 6-18 to 6-21
Flowmeter, orifice-type, 6-21, 6-22, 6-23, 6-24

Flowmeter, rotameter, 6-21, 6-22, 6-23, 6-24
Flowmeter, venturi type, 6-21, 6-22, 6-23, 6-24
Fluid separator and dump trap, 6-36 to 6-37
Flux density, 1-28
Focusing, 4-42
Forced-air cooling, 6-2
Foundation machining, 7-17 to 7-18
Frame of reference, 7-2 to 7-3
Frequency response, 1-41 to 1-42
Frequency synthesizers, 4-60 to 4-62
Frequency utilization, 4-3
Function priority circuits, 3-46
Functional description of computer Mk 152, 3-3 to 3-20
Fundamentals of ferromagnetism, 5-34 to 5-35

G

Gain compensating resistor, 2-17 to 2-18
Gain control, 4-66
Gain, phase, and balance adjustments, 1-37
General-purpose computer, 3-2
Generator, 3-61
GFCS Mk 68 collimation, 8-20
Glossary, AI-1 to AI-18
Glow discharge, 5-45
Graduated drum, 7-8
Group velocity, 5-15
Guidance beam boresight, 8-20 to 8-23
Gunner's quadrant, 7-9 to 7-10

H

H register, 3-33
Heat exchangers, 6-9 to 6-12
Heterodyning, 4-54
Hilger and Watts TB4, 7-10
Horizon checks, 7-20, 7-23, 7-24
Horizon effect, 4-7 to 4-8
Horizontally polarized, 4-5
Hunting, 1-38
Hybrid junctions, 5-25 to 5-30
Hybrid mixer, 4-63
Hybrid ring, the, 5-29 to 5-30
Hybrid, 3-DB, 5-33
Hydraulic transmission assembly, 1-10
Hyperbolic dielectric surface, 8-8
Hysteresis, 1-30
Hysteresis loop, 5-41

I

IF amplifiers, 4-64 to 4-66
Impedance changing devices, 5-19 to 5-20
Inclination verification, 7-17
Index Adder, 3-33
Index control register, 3-12
Index of refraction, 4-3
Indexing, 3-34
Inertia, 1-18
Input cavity (buncher), 4-37
Input control circuits, 3-47
Input data functions, 3-45
Input/output console, 3-57 to 3-59
Input/output section, 3-14 to 3-20
Instruction format, 3-26 to 3-30
Instruction repertoire, 3-5
Integrated maintenance, 9-4 to 9-5
Interaction space, 4-25
Interequipment leveling, 7-18
Interrupt Entrance Register, 3-10
Interrupts, 3-8
Intersystem designation test, 9-7
Inverse sine and cosine loops, 2-34 to 2-35
Inverse square law, 4-6
I/O adapter (IOA), 3-47 to 3-49
I/O controller, 3-39 to 3-47
Iris, 5-20
Isolation amplifiers, 1-31 to 1-33, 2-27

K

K designators, 3-26
K register, 3-13, 3-32, 3-37, 3-41
Keep-alive voltage, 5-45
Keyboard printer, 3-58
Kirchhoff's Law, 2-13, 2-20
Klystron amplifiers, 4-36 to 4-47

L

Leak detector, 6-13
Lens antenna, 5-49 to 5-51
Leveling screws, 7-6
Levels, 7-10

Linear displacement, 7-5
Linear detector, 4-67
Linear-beam tubes (O type), 4-36 to 4-51
Liquid cooling, 6-4
Liquid cooling systems, types of, 6-4 to 6-9
Lissajous pattern, 2-31, 8-24
LNA, 4-54, 4-62
Local oscillator, 4-56 to 4-60
Logarithmic detector, 4-68
Logarithmic functions, 2-36 to 2-37
Logarithmic IF amplifiers, 4-66 to 4-67
Logic control, 3-57

**M**

M designator, 3-28
Magic T, the, 4-63, 5-28 to 5-29
Magnetic amplifiers, 1-28 to 1-31
Magnetic domain, 5-34
Magnetic field, the, 5-8 to 5-9
Magnetrons, 4-24 to 4-34
Main memory address register, 3-42, 3-43
Maintenance, 9-1 to 9-31
  fault isolation, 9-5 to 9-29
    fault isolation tools, 9-7 to 9-29
      combat system tests, 9-7
      diagnostic testing programs, 9-11 to 9-12
      maintenance support documentation, 9-12 to 9-29
      on-line/off-line testing, 9-8 to 9-11
      subsystem tests, 9-7 to 9-8
  planned maintenance system (PMS), 9-1 to 9-5
    integrated maintenance, 9-4 to 9-5
      combat system testing, 9-4 to 9-5
      equipment level testing, 9-5
      subsystem testing, 9-5
    maintenance data system (MDS), 9-4
      data processing, 9-4
      recording, 9-4
Maintenance—Continued
  planned maintenance system (PMS)—Continued
    maintenance scheduling, 9-2 to 9-3
      cycle schedule, 9-2
      maintenance control board, 9-3
      Maintenance Index Pages (MIPs), 9-2
      quarterly schedule, 9-2
      weekly schedule, 9-3
    PMS objective, 9-2
  summary, 9-29
Maintenance responsibility, cooling system, 6-32
Mandrel, 2-5
Masers, 4-54
Master reference plane, 7-16 to 7-17
Matched filter, 4-70
MDS, 4-8, 9-4
Mechanical scanning, 4-12 to 4-15
Memory capacities and special addresses, 3-6 to 3-7
Memory lock-out (MLO), 3-35
Memory section, 3-14
Metallic insulator, 5-3, 5-4
Methods of coupling, 5-16 to 5-17
Micrometer microscopes, 7-6
Microwave components, 5-1 to 5-57
  antennas, 5-46 to 5-56
    lens antenna, 5-49 to 5-51
    parabolic reflectors, 5-47 to 5-49
    phased arrays, 5-51 to 5-56
  cavity resonators, 5-22 to 5-25
    cavity coupling, 5-25
    cavity tuning, 5-24 to 5-25
  directional couplers, 5-30 to 5-43
    Bethe-hole coupler, 5-32
    bidirectional coupler, 5-31 to 5-32
    faraday rotation, 5-36 to 5-38
    ferrite attenuator, 5-35
    ferrite isolator, 5-38
    ferrites, 5-33 to 5-34
    fundamentals of ferromagnetism, 5-34 to 5-35
      electron motion, 5-34 to 5-35
      ferrite materials, 5-35
    nonreciprocal isolator, 5-35 to 5-36
    phase shifters, 5-41 to 5-43
      antenna phase shifter, 5-41 to 5-43
      ferrite phase shifters, 5-41

Microwave components—Continued
  directional couplers—Continued
    3-DB hybrid, 5-33
    two-hole directional coupler, 5-30 to 5-31
    variable attenuator, 5-38 to 5-41
  duplexers, 5-43 to 5-45
    ATR tube, 5-45
    balanced duplexer, 5-45
    passive TR limiter, 5-45
    shutters, 5-45
    TR tube, 5-44 to 5-45
  hybrid junctions, 5-25 to 5-30
    hybrid ring, the, 5-29 to 5-30
    magic T, the, 4-63, 5-28 to 5-29
    T junctions, 5-26 to 5-28
  summary, 5-56 to 5-57
  waveguide theory of operation, 5-1 to 5-22
    behavior of electromagnetic waves within a waveguide, 5-12 to 5-15
    bends, twists, and joints, 5-17 to 5-19
    development of waveguides from parallel lines, 5-3 to 5-4
    effect of a waveguide on different frequencies, 5-4 to 5-5
    electromagnetic fields in a waveguide, 5-5 to 5-10
      boundary conditions, 5-9 to 5-10
      electric field, the, 5-6 to 5-8
      magnetic field, the, 5-8 to 5-9
    impedance changing devices, 5-19 to 5-20
    methods of coupling, 5-16 to 5-17
    modes of operation, 5-10 to 5-12
      dominant mode, 5-10 to 5-11
      mode numbering system, 5-11 to 5-12
    terminating a waveguide, 5-20 to 5-22
Microwave power meter, 8-14 to 8-16
Minimum detectable signal to noise ration, 4-8
Miss distance, 8-9
Mk 152, digital computer, 3-2 to 3-20
Modulators, 1-21 to 1-23, 4-51 to 4-54
Moisture monitor, 6-41 to 6-42
Monitor mode, 3-45
Monopulse, 4-15
Motor, 3-61
Motor control, 3-61
Motor/generator (MG) set, 3-60 to 3-62
Moving target indication, 4-21
MTI, 4-21, 4-23
Multiplication and division operations, 2-20 to 2-25
Multiplication of two variables with a potentiometer, 2-20 to 2-21
Multiturn potentiometers, 2-9 to 2-10

N

Narrow band filter, 4-73
Nautical mile, 4-5
NDRO, 3-6, 3-21, 3-32, 3-34
Negative resistance, 4-27
Noise, 4-8, 4-46
Nonreciprocal isolator, 5-35 to 5-36
Normal, 5-14
Null (nulls, nulled), 1-4, 1-9, 1-11, 1-15, 1-17, 1-26, 1-37
Nutating waveguide, 4-13
Nutation, 4-13

O

Ohm's law, 1-15
One-shot circuits, 3-46
On-line/off-line testing, 9-8 to 9-11
Open loop system, basic operating principle of the, 1-1
Operational accuracy, 1-36 to 1-41
Operational amplifiers, 2-35 to 2-37
Operator controls, 3-21 to 3-24
Optical axis, 8-1
Optical targets, 8-10
Order signal, 1-4
Orifice plate, 6-18
Original alignment, 7-1
Output cavity (catcher), 4-39
Output control circuits, 3-47
Output data functions, 3-45
Overall combat system operability test OCSOT, 9-5
Oxygen analyzer, 6-29

P

Parabolic reflectors, 5-47 to 5-49
Parabolic surface, 8-7
Parallax corrections, 7-5
Parallel planes, 7-2
Parallel resistor networks, 2-11 to 2-17
Parallelism, establishment of, 7-17 to 7-18
Parametric amplifiers, 4-54
Passive TR limiter, 5-45
Peak power, 4-9
Performance of fire control radar rf-optical alignment, 7-18
Performance of train and elevation space alignment (star checks), 7-18
Peripheral equipment, 3-57 to 3-62
PFN, 4-51, 4-52, 4-53, 4-54
Phase error, 8-9
Phase shifters, 5-41 to 5-43
Phase velocity, 5-15
Phase-lock loop (PLL), 4-61
Phase-sensitive detector, 4-68 to 4-69
Phased arrays, 5-51 to 5-56
Phasing, 4-16
Pi mode, 4-32
Planned maintenance system (PMS), 9-1 to 9-5
PMS objective, 9-2
POFA, 9-7
Point contact diode, 4-62
Pointing line, 7-2
Polarization converter, 8-8
Position servo operation, 1-13 to 1-15
Potentiometers, 2-5 to 2-10
Power combiner, 5-56
Power systems, 1-7 to 1-13
Preamplifiers, 1-25
Precision attenuators, 8-13, 8-24
Pressure regulator, 6-38 to 6-39
PRF, 4-9
Primary cooling system, 6-4 to 6-8
Priority circuits, 3-46
Privileged instructions, 3-30
Probability of detection, 4-8
Processing and detecting echo signals, 4-8 to 4-11
PRT, 4-9
Pseudorandom codes, 4-71
Pseudorandom sequences, 4-71
Pulse compression, 4-10, 4-69 to 4-74
Pulse forming network, 4-51, 4-52, 4-53, 4-54
Pulse radars, 4-11 to 4-12
Pulse repetition frequency (PRF), 4-9
Pulse repetition time, 4-9
Pulse track boresight, 8-26
Pulse track angle sensitivity, 8-26
Pulse transformer, 4-51, 4-52, 4-53, 4-54
Pulse-Doppler radar, 4-20 to 4-24
Pulsewidth (radar), 4-6

Q

Quadrature, 1-33, 4-72
Quarterly schedule, 9-2

R

Radar beacon test set AN/TPN-7, 8-16
Rate computing loops, 2-35
Rate generators, 2-10 to 2-11
Radar collimation requirements, 8-3 to 8-9
Radar collimation shore tower, 8-10 to 8-16
Radar dry-air system, 6-32 to 6-43
Radar principles, 4-1 to 4-82
  electronic warfare, 4-74 to 4-80
    electronic counter-countermeasures (ECCM), 4-77 to 4-80
      antenna ECCM, 4-77
      ECM-ECCM matrix, 4-79 to 4-80
      other ECCM, 4-79
      receiver/signal processor ECCM, 4-77 to 4-79
      transmitter ECCM, 4-77
    electronic countermeasures (ECM), 4-76 to 4-78
      active deception, 4-76
      active denial ECM, 4-76
      passive deception, 4-76 to 4-78
      passive denial, 4-76
  radar basics, 4-1 to 4-11
    basic radar principles, 4-5 to 4-6
      radar classifications, 4-5
      radar resolution and ambiguities, 4-6
      target location, 4-5 to 4-6
      target velocity, 4-6

Radar principles—Continued
  radar basics—Continued
    decibels, 4-1 to 4-3
    frequency utilization, 4-3
    frequency, wavelength, and velocity, 4-3
    processing and detecting echo signals, 4-8 to 4-11
      antenna factors, 4-10 to 4-11
      target cross section, 4-11
      transmitter power, 4-8 to 4-10
    wave polarization, 4-3 to 4-5
    wave propagation, 4-6 to 4-8
      atmospheric absorption, 4-7
      horizon effect, 4-7 to 4-8
      refraction, 4-7
  radar systems, 4-11 to 4-24
    cw radar, 4-18 to 4-20
      cw radar, 4-19 to 4-20
      Doppler, 4-18 to 4-19
      FM-cw radars, 4-20
    pulse-Doppler radar, 4-20 to 4-24
      pulse-Doppler theory, 4-21 to 4-24
    pulse radars, 4-11 to 4-12
    scanning, 4-12 to 4-18
      electronic scanning, 4-15 to 4-18
      mechanical scanning, 4-12 to 4-15
  receivers, 4-54 to 4-74
    radar displays, 4-74
    receiver system functional areas, 4-54 to 4-74
      automatic frequency control (AFC), 4-55 to 4-56
      detectors, 4-67 to 4-68
      frequency synthesizers, 4-60 to 4-62
      gain control, 4-66
      IF amplifiers, 4-64 to 4-66
      local oscillator, 4-56 to 4-60
      logarithmic IF amplifiers, 4-66 to 4-67
      phase-sensitive detector, 4-68 to 4-69
      pulse compression, 4-69 to 4-74
      radar receiver mixers, 4-62 to 4-64

Radar principles—Continued
  summary, 4-80 to 4-82
    electronic warfare (EW), 4-82
    radar systems, 4-81
    receivers, 4-82
    transmitters, 4-81 to 4-82
  transmitters, 4-24 to 4-54
    crossed-field tubes (M type), 4-24 to 4-36
      crossed-field amplifier (CFA), 4-34 to 4-36
      magnetrons, 4-24 to 4-34
    linear-beam tubes (O type), 4-36 to 4-51
      klystron amplifiers, 4-36 to 4-47
      traveling-wave tube (TWT), 4-47 to 4-51
    modulators, 4-51 to 4-54
Radar range, 4-5
Radar receiver mixers, 4-62 to 4-64
Radar test set AN/SPM-9, 8-12 to 8-13
Radial displacement, 8-22
Radiation losses, 5-2
RAM (radar absorbing material), 4-76
Random access memory (RAM), 3-52
Range calibration set AN/SPM-6 series and AN/UPM-115, 8-13 to 8-14
Read cycle, 3-50
Read Only Memory (ROM), 3-32
Rear reference (missile), 8-3
Receive beamformer, 5-56
Receiver system functional areas, 4-54 to 4-74
Receivers, 4-54 to 4-74, 4-82
Reentrant, 4-24
Reference frame, 7-2
References, AII-1 to AII-6
Reflex klystron, 4-56 to 4-60
Refraction, 4-5, 4-7
Refraction, heat, 8-17
Refractive index, 4-7
Refrigerant, 6-33
Repeller, 4-56
Request circuits, 3-47
Requestor hold, 3-52
Resistivity, 6-28
Resolution, 2-31 to 2-32
Resolver, 1-31
Response curves, 4-65, 4-66
Response servo, 1-2, 1-38
Response time, 1-38
Resume, 3-11

Roller path inclination analysis, 7-23 to 7-28
Rotating joint, 5-19
RPP inclination verification, 7-20 to 7-22

S

s designators, 3-26
Saturation point, 1-29
Scale changing (multiplication and division), 2-14 to 2-17
Scale factors, 2-2 to 2-4
Scanning, 4-12 to 4-18
Scheduling, maintenance, 9-2 to 9-3
Seawater strainers, 6-13 to 6-15
Secondary cooling system, 6-8
Self-contained optics, 7-12
Sensing elements, 1-19
Sequencer, 3-12
Serializer, 3-58 to 3-59
Serpentine feed, 5-52
Servo error signal, 1-2, 1-4, 1-14, 1-15, 1-17, 1-19, 1-21, 1-23, 1-24
Servomechanisms, 1-1 to 1-43
  control systems, 1-1 to 1-7
    basic operating principle of a closed loop system (servo), 1-1 to 1-15
      functional sections of a servo, 1-3 to 1-4
      servomechanism characteristics, 1-2 to 1-3
      signal types, 1-4 to 1-5
    basic operating principle of the open loop system, 1-1
    control systems terminology and symbols, 1-5 to 1-7
      schematic and block diagrams, 1-5 to 1-6
      symbols and definitions, 1-6 to 1-7
      system type identification, 1-7
  operational accuracy, 1-36 to 1-41
    frequency response, 1-41 to 1-42
    gain, phase, and balance adjustments, 1-37
    hunting, 1-38
    response time, 1-38
    stabilization through damping, 1-38 to 1-41
      error-rate damping, 1-40 to 1-41
      viscous damping, 1-39 to 1-40
Servomechanisms—Continued
  power systems, 1-7 to 1-13
    electric servo, 1-8
    electrohydraulic servo, 1-9 to 1-13
      hydraulic transmission assembly, 1-10
      servo control loop, 1-11 to 1-13
    electromechanical servo, 1-8 to 1-9
  servo circuits, 1-19 to 1-36
    comparison of ac and dc servos, 1-36
    demodulators, 1-23 to 1-25
      diode demodulators, 1-23 to 1-24
      electric demodulator, 1-24 to 1-25
    modulators, 1-21 to 1-23
      electron tube modulators, 1-22 to 1-23
      semiconductor diode modulator, 1-22
    sensing elements, 1-19
      potentiometers, 1-19
      variable transformers, 1-19
    servoamplifiers, 1-25 to 1-36
      amplidynes, 1-33 to 1-36
      electron tube servo amplifier, 1-26 to 1-28
      isolation amplifiers, 1-31 to 1-33
      magnetic amplifiers, 1-28 to 1-31
      preamplifiers, 1-25
      transistor power amplifier, 1-25 to 1-26
    synchronizing circuits, 1-19 to 1-21
      relay-operated synchronizing circuit, 1-20 to 1-21
      semiconductor diode synchronizing network, 1-21
  servo operation, 1-13 to 1-19
    acceleration servo operation, 1-17
    operational characteristics, 1-17 to 1-19
    position servo operation, 1-13 to 1-15
    velocity servo operation, 1-16 to 1-17
  summary, 1-41 to 1-42
Servo multiplier, 2-25 to 2-27
Set resume, 3-20
Ship's base plane, 7-16
Ship's air supply, 6-33
Shutters, 5-45
Side lobes, 4-10
Sigma, 1-6, 1-14

Sign reversing loop with unity gain, 2-13 to 2-14
Signal comparator, 8-13
Silicone grease, 6-2
Sine and cosine potentiometers, 2-10
Sine bar, 7-10
Skin effect, 5-3
Skip on no resume, 3-20
Smooth log, 7-29
Special-purpose computer, 3-2
Special register, 3-12
Spectrum analyzer, 8-13
Spherical coordinate system, 7-2
Stabilization through damping, 1-38 to 1-41
Stabilized local oscillator, 4-23
Stabilized master oscillator, 4-23
STALO, 4-23
STAMO, 4-23
Standing wave ratio (SWR), 5-20
Star checks, 7-23
START signal, 3-31
Static parallax, 7-5
Stator windings, 1-8
STC (sensitivity time control), 4-66, 5-41
Summation of voltages with dissimilar scale factors, 2-19 to 2-20
Summation operations, 2-18 to 2-20
Summing amplifier, 2-12 to 2-13
Support documentation, maintenance, 9-12 to 9-29
Subsystem testing, 9-5
Subsystem tests, 9-7 to 9-8
Swamping resistor, 4-65
Synchronization indicator, 8-13
Synchronizing circuits, 1-19 to 1-21
Synchronous tuning, 4-41
System components, cooling, 6-9 to 6-32
Systems, radar, 4-11 to 4-24, 4-81

T

T junctions, 5-26 to 5-28
Tape punch, 3-57 to 3-58
Tape reader, 3-58
Target cross section, 4-11
Target location, 4-5 to 4-6
Target velocity, 4-6
TARTAR collimation procedures, 8-18 to 8-20
Teflon® tape, 6-21
Telltale oil filter and dump trap, 6-37 to 6-38
Temperature gradient, 6-11
Temperature regulating valves, 6-15 to 6-18
Terminating a waveguide, 5-20 to 5-22
TERRIER collimation procedures, 8-20 to 8-27
TERRIER GMFCS collimation requirements, 8-4 to 8-9
Test equipment, collimation, 8-10 to 8-16
Theodolite, 7-6 to 7-7
Tools, fault isolation, 9-7 to 9-29
Tower array, 8-10
TR tube, 5-44 to 5-45
Track receive axis (TR), 8-4
Track receive (TR) axis collimation, 8-18
Track transmit axis (TX), 8-4
Track transmit (TX) axis collimation, 8-18 to 8-19
Train angles, 7-2
Tram bar and tram blocks, 7-12 to 7-15
Transducer, 1-6, 1-14, 1-19
Transient distortion, 4-65
Transistor power amplifier, 1-25 to 1-26
Transit LOS, 7-6
Transits, 7-6
Transmitter power, 4-8 to 4-10
Transmitters, 4-24 to 4-54, 4-81 to 4-82
Trapped rays, 4-7
Traveling-wave tube (TWT), 4-36, 4-47 to 4-51
Trigonometric functions, 2-27 to 2-35
TWT, 4-36, 4-51
Two-hole directional coupler, 5-20 to 5-31
Type I cooling system, 6-8 to 6-9
Type II cooling system, 6-9
Type III cooling system, 6-9

U

U, R, P selector, 3-33
Unit functional description, AN/UYK-7(V), 3-24 to 3-57

V

Variable attenuator, 5-38 to 5-41
Variable orifice, 6-19

Vector, 1-4
Velocity modulation, 4-39
Velocity servo operation, 1-16 to 1-17
Vertical polarization, 8-8
Vertically polarized, 4-5
Viscous damping, 1-39 to 1-40
Voltage regulator, 3-62

W

Wave polarization, 4-3 to 4-5
Wave propagation, 4-6 to 4-8
Waveguide, 5-2
Waveguide flooding, 6-42 to 6-43
Waveguide theory of operation, 5-1 to 5-22
Weapon control reference plane, 7-17
Weapons system smooth record, 7-29 to 7-30
Weekly schedule, 9-3
Working electrons, 4-31
Write cycle, 3-50

X

X-rays, 4-41

Z

Zm register, 3-14

☆U.S. GOVERNMENT PRINTING OFFICE: 1985-631-087:20053

UNIVERSITY OF ILLINOIS-URBANA
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